Two Sections—Section 1

Electrical Engineering

December
1939

Published Monthly by the
American Institute of Electrical Engineers

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NEW G-E VARMETER Measures Reactive Kva in 10 Minutes!

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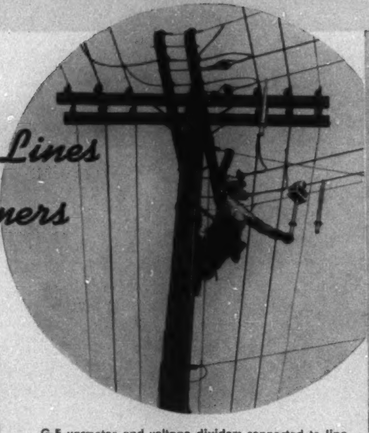
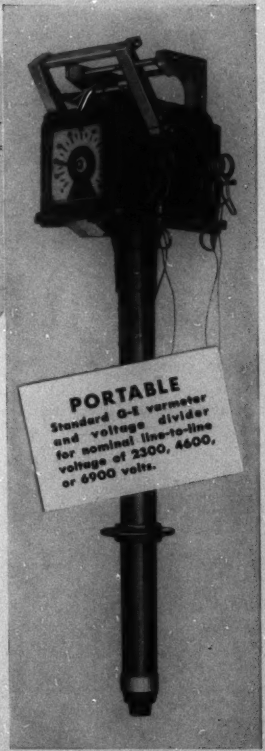
No Transformers



G-E varmeter and voltage dividers connected to line


PORTABLE
Standard G-E varmeter and voltage divider for nominal line-to-line voltage of 2300, 4600, or 6900 volts.

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TO help you bring your lines nearer unity power-factor—by aiding you in placing capacitors intelligently—that's the principal purpose of General Electric's new varmeter!

It offers the simplest and quickest portable means of measuring vars (reactive volt-amperes). You can set it up and get a reading in 10 minutes.

WHAT IT DOES—The G-E portable varmeter permits quick determination of current up to 300 amperes. And, by using voltage dividers, you can measure line volts, and vars—both lagging and leading—without complicated readings, without expensive equipment, without cutting into the line.

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Find out the facts about your lines with this new G-E varmeter—it can obtain measurements for you that heretofore involved great cost and labor. It will point out simply, accurately, and quickly how you can serve more pay load with your lines.

FOR FURTHER INFORMATION—Ask for our publication GEA-3294, which contains complete information. Call your nearest G-E office or write General Electric, Schenectady, N. Y.

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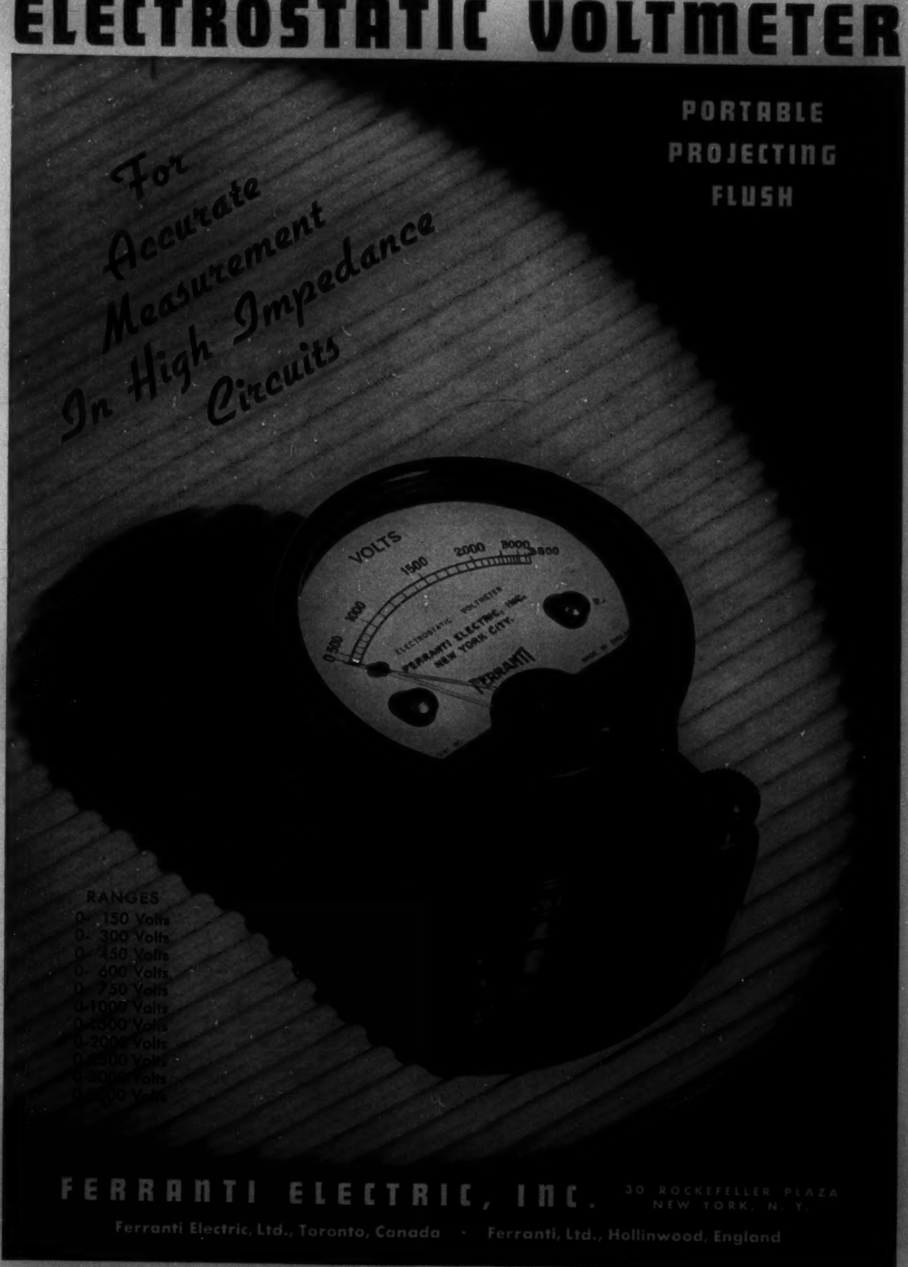
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*TYPHONITE ELDORADO PENCIL PAGE

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Ratio-Differential Pilot Wire Protective Relay Circuits

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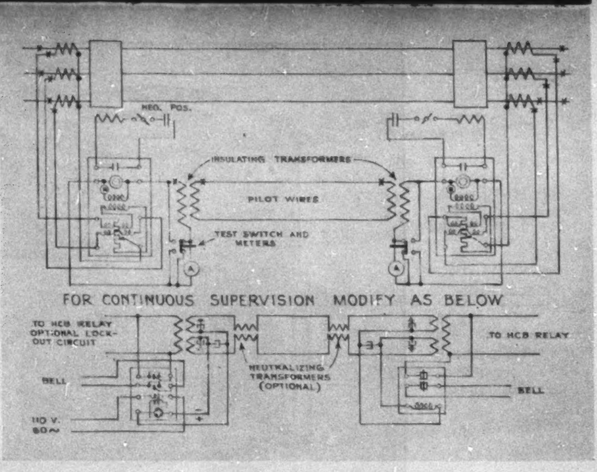
NEG. POS.
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PILOT WIRES
TEST SWITCH AND METERS
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TO HCB RELAY OPTIONAL LOCK-OUT CIRCUIT
NEUTRALIZING TRANSFORMERS (OPTIONAL)
TO HCB RELAY
BELL
BELL
110 V. 60~

This Typhonite Eldorado drawing shows the application of a new relay for "ratio-differential pilot wire protection" of an electric power transmission circuit. For a circuit of this nature, the idea of comparing voltages, currents or power from both ends of a transmission line section through the medium of pilot wires, or indirectly by use of carrier-current signals, has long been used as a means of detecting transmission line faults.

This relay and circuit accomplish desirable simplification in both circuit and equipment, with consequent improvement in character and dependability of operation. The specific relay involved in the circuit has been developed by Westinghouse and is known as "type HCB."

FREE: A blueprint of this circuit made directly from the original drawing will be sent upon request. Just write to Pencil Sales Department, JOSEPH DIXON CRUCIBLE COMPANY, Jersey City, N. J. for blueprint No. 42-J12. And note the ideal blueprint resulting from Typhonite Eldorado's clean, opaque lines.

***TYPHONITE** is a new form of natural graphite, used exclusively by Dixon in making leads for Eldorado Pencils. Typhonite consists of extremely minute particles produced by a whirlwind or typhoon of dry steam. This new exclusive Dixon process is one of the reasons why Eldorado pencils hold their points longer, give off freely, and make such opaque lines and figures.

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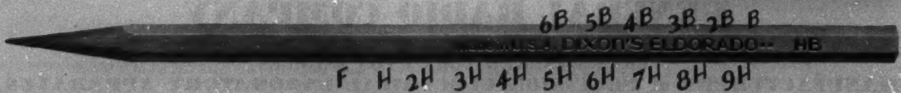
6B 5B 4B 3B 2B B
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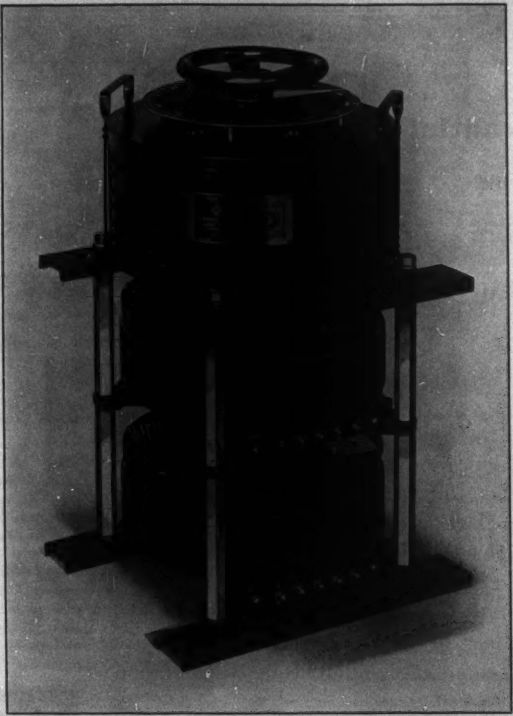
F H 2H 3H 4H 5H 6H 7H 8H 9H

HIGH POWER VARIACS



FOR HIGH POWER APPLICATIONS two- and three-gang assemblies of the new Types 50-A 50-B VARIACS are now available on special order with prompt deliveries. When used on three-phase circuits in Delta or Wye connections, really high power can now be controlled with all of the conveniences found in the standard low-power VARIACS: excellent regulation; perfectly smooth and stepless control of output voltage from zero; very high efficiency; relatively small size; linear output voltage with calibrated dials; small temperature rise and advanced mechanical design.

The ganged units are shipped for table mounting unless specified otherwise. The standard shaft will accommodate a panel thickness up to one and one-half inches; longer shafts for thicker panels are supplied upon order without extra charge. The ganged assemblies of the Type 50 VARIACS cannot be used on vertical panels without auxiliary bracing.

Specifications

TYPE	DESCRIPTION	LINE VOLTAGE	MAX. CURRENT	LOAD RATING	PRICE
50-AG-2	Two Type 50-A	115-v*	45 amp	9 kw	$225.00
50-BG-2	Two Type 50-B	230-v*	31 amp	12 kw	225.00
50-AG-3	Three Type 50-A	230-v†	45 amp	18 kw	335.00
50-BG-3	Three type 50-B	440-v†	31 amp	24 kw	335.00

* Delta (open or closed). † Wye.

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Electrical Engineering

Registered U. S. Patent Office

for December 1939—

The Cover: Sodium-vapor luminaires cast their golden brilliance over the new Main Avenue Bridge in Cleveland, Ohio. This is one of the many notable lighting installations mentioned in the current progress report of the AIEE committee on the production and application of light (see pages 497–508) Westinghouse Photo

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¶ Statements and opinions given in articles and papers appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility.

¶ Correspondence is invited on all controversial matters.

High Lights

Carrier System. A new 12-channel carrier telephone system for open-wire lines was first placed in commercial operation in Texas in 1938; various special problems arose in the application of the system to existing open-wire lines (*Transactions pages 666–74*). Increasing the transmission frequency range of the wire lines produced new problems with respect to attenuation, noise, and cross talk which were solved by modifications of construction, new transposition designs, improvement of impedance matches in parts of the circuit, and closer repeater spacings (*Transactions pages 656–65*).

Progress in Illumination. For many years, light sources and their application have undergone rapid changes as scientists and illuminating engineers sought improved and more efficient means of producing light and more effective ways of applying it. To provide a continuing record of that progress the AIEE committee on production and application of light has prepared at periodic intervals reports reviewing progress in this rapidly advancing field. The current report records the achievements of the past three years (*pages 497–508*).

Impedance Relays. High-speed impedance or reactance relays on a tie circuit between two systems will operate if the systems pull out of step, the indication being the same as though a fault existed; various blocking schemes have been devised to prevent such operation. In one recently applied, out-of-step blocking and selective tripping are obtained with existing relays and without the use of carrier current or pilot wires (*Transactions pages 637–46*).

Network Experience. The low-voltage a-c distribution network established in the central business district of the city of Philadelphia, Pa., some 12 years ago differs fundamentally from the more usual types of networks; it consists of a number of interlaced loop primary feeders, sectionalized by automatic oil circuit breakers, supplying a fused secondary network (*pages 517–21*).

Spectator Conveyer. During the 1939 season, more than 5,000,000 visitors to the General Motors "Futurama" at the New York World's Fair were transported through the exhibit on a specially designed conveyer consisting of a continuous chain of armchairs. An intricate sound system brought to each spectator a running account of the scene as it unfolded before him (*pages 509–14*).

Cable Loading. For a given load cycle and ambient temperature, ratings of cables installed in underground ducts will vary with the number of cables installed in the duct bank and its size. A study of economical loading has been made for cables in New York having a voltage range from 13.6 to 132 kv (*Transactions pages 611–18*).

Dielectric Strength. Porcelain suspension-insulator shells submerged in oil have been subjected to high-voltage breakdown tests to determine the impulse strength for both limited and repeated applications and the 60-cycle strength; ability to withstand stresses from steep-front lightning strokes is demonstrated (*Transactions pages 651–6*).

Condenser Bushings. Protection of the paper insulation in bushings of the condenser type from external influences is necessary in order to obtain long life. Improvements have been made in impregnating and varnish treatments, gasket materials, and weather-casing design (*Transactions pages 646–50*).

Human Science. It has been said that man has mastered the machine but has not yet mastered himself, which points to the need for more attention to the study of anthropology—the human science. In this issue, an AIEE member presents some thoughts on the subject (*pages 515–16*).

United Engineering Trustees. Officers were elected and annual reports were presented at the recent annual meeting of United Engineering Trustees, Inc., joint agency of the Founder Societies, by UET and its departments, The Engineering Foundation and Engineering Societies Library (*pages 530–4*).

Winter Convention. An address on atomic disintegration by Nobel Prize Winner Enrico Fermi will be a feature of the AIEE 1940 winter convention to be held in New York, N.Y., January 22–26. For the technical program, 19 technical sessions and 5 technical conferences are planned (*page 522*).

Ignitrons. The ignitron type of mercury-arc rectifier, which uses a high-resistance rod immersed in the mercury to initiate the arc, may be made in sizes large enough for railway service; voltage drop in the arc is less than that in the conventional rectifier (*Transactions pages 618–24*).

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Ultrahigh-Speed Reclosing. Experience with re-energization of high-voltage transmission circuits in from 10 to 14 cycles after occurrence of a fault has justified the original expectation of a 75-per-cent reduction in outages on a 132-kv system (*Transactions pages 625–36*).

Corrections. TRANSACTIONS section, October 1939 issue, page 525, Lichtenberg discussion: Radio Manufacturers Association should be *Refrigeration Machinery Association;* American Cotton Manufacturers Association should be *Air Conditioning Manufacturers Association.* Contrary to the report published on page 483 of the November issue, the AIEE Student Branch of the University of Cincinnati *was* represented at the District conference of Branch officers held at Scranton, Pa., October 12, 1939—by Branch Chairman G. W. Little.

Coming Soon. Among special articles and technical papers now undergoing preparation for early publication are: a report prepared by the AIEE committee on power generation reviewing progress in that field during the past six years; an article reviewing a quarter-century of transcontinental telephony, by Past-President F. B. Jewett; an article discussing the various uses of electricity in chemical plants, by Kennard Pinder (M'37); a paper describing turbine-electric textile-range drives by E. L. Richardson; a paper discussing the characteristics and power requirements of spinning frames by E. A. Untersee; a paper on modern trends of low-voltage air circuit breakers by J. W. Seaman (A'32); a paper describing electrical equipment on machine tools by B. P. Graves; a paper on the measurement of carrier-current losses and minimization of interference on the Boulder Dam-Los Angeles transmission lines by J. D. Laughlin (A'36), W. E. Pakala (A'38), and M. E. Reagan (M'30); a paper discussing some factors in the mechanical design of high-speed turbogenerators by S. H. Mortensen (F'20) and James J. Ryan; a paper on special problems of two-pole turbine generators by C. M. Laffoon (M'39) and B. A. Rose; papers on hydrogen-cooled turbine generators by M. D. Ross (A'23) and C. C. Sterrett, and D. S. Snell (A'24); a paper on recent developments in telegraph switching by F. E. d'Humy (F'30) and H. L. Browne; a paper describing a high-gain d-c amplifier for bioelectric recording by Harold Goldberg (A'35); a paper describing the signal system, interlocking plants, and automatic train control on the San Francisco-Oakland Bay Bridge railway by C. R. Davis (A'36); a paper on electrical engineering and the petroleum refiner by G. R. Weeks, H. W. Giesecke (A'35), and C. M. Lathrop; and a report on progress of the art in electrical machinery, 1934–39, by an AIEE committee.

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Progress in the

Production and Application of Light

A. L. POWELL
FELLOW AIEE

For at least three decades, light sources and their application continuously have undergone rapid changes. To provide the Institute membership with a record of these developments, it has been the policy of the AIEE committee on the production and application of light to prepare at periodic intervals reports reviewing the progress achieved during those intervals. The 1939–40 committee[*] presents in this report a summary of the epoch-making advancements since 1936, when the last previous report was published,[1] prepared by a member and former chairman of the committee.

THERE have been numerous developments in the art of lighting during the past three years, but to the illuminating engineer this is nothing unusual. For at least three decades light sources and their application have always undergone rapid changes. It is true that the whole field of electrical engineering, being young and with a tremendous horizon, is in a constant state of flux, but those working in lighting have reason to feel particularly proud of the way that new frontiers have been attacked. To say the least, lighting is not static and those engaged in it are constantly experiencing the thrill that comes with change.

During the period under consideration there have been some epoch-making developments and numerous others that were foretold in the previous report. These take the nature of refinement and expansion of ideas promulgated several years ago.

In the last report it was pointed out that during the year 1935 more than 700 million incandescent lamps were sold, which was then a new high record. In 1936 this figure was exceeded, the total reaching 880 million. The year 1937 saw an all-time high of 955 million, and in 1938 there was a falling off to approximately 800 million; of this total, 60 per cent was what are called large and 40 per cent miniature lamps. The rate for 1939 to date indicates that this figure will be exceeded.

New Incandescent Lamps

LAMPS FOR PHOTOGRAPHY

There probably has never been a period that has shown such a great growth in public interest in any hobby. Almost everyone is a camera enthusiast. The development of numerous types of inexpensive miniature cameras, of new types of film, of practical color film, and simple movie cameras has contributed to this end. Most of the amateur photographers are not content with natural light, but are riding their hobby for 24 hours a day. The so-called photoflash lamp has completely displaced the old magnesium flash bag, and the news and commercial photographers are requiring many forms of flash lamps. The new varieties of color film have presented lighting problems. The miniature camera has greatly increased the importance of enlarging. As a result of all this, the line of lamps designed especially for photography has grown by leaps and bounds.

The photoflood lamp series has been supplemented by three sizes, 250, 500, and 1,000 watts in blue bulbs for use with "regular" Kodachrome film. These also find application in indoor photography where artificial light is required to supplement daylight.

A 500-watt photoflood lamp with an inside aluminized reflecting surface is on the market and proves very convenient and compact.

Three years ago three sizes of photoflash lamps were listed which had bulbs loosely filled with very thin sheets of aluminum foil in an atmosphere of oxygen. This general form has been supplemented by lamps using extremely fine aluminum wire instead of foil, and the entire line has been expanded so that now no less than eight types and sizes of photoflash lamps designed for particular operating conditions are available. Space does not permit an analysis of details of their characteristics.

For amateur and professional photoenlarging there is now standardized a line of seven lamps in special white bulbs varying in size from a tiny *S*-11[†] bulb emitting 1,125 lumens to a *PS*-30 bulb emitting 15,800 lumens.

Since color photography requires light of a definite spectral composition for proper rendition, it has been necessary to make available lamps standardized to operate at a predetermined color temperature, namely, 3,200 degrees Kelvin. These, again, are of various forms and sizes (500 to 5,000 watts) and are 13 in number.

Certain classes of color photography require light sources at a still higher color temperature and five lamps (1,000 to 10,000 watts) are available that are designed to operate at 3,380 degrees Kelvin.

LUMILINE LAMPS

These tubular lamps with contacts at both ends are still quite popular where structural conditions make neces-

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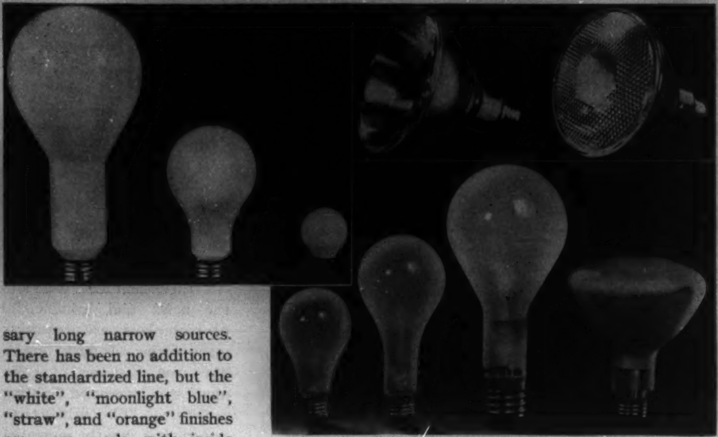
[*] **Personnel of AIEE Committee on Production and Application of Light:** D. W. Atwater, *chairman;* S. K. Barrett, Robin Beach, W. T. Blackwell, H. B. Dates, E. E. Dorting, C. L. Dows, L. R. Gamble, C. A. B. Halvorson, Jr., L. A. Hawkins, S. G. Hibben, W. C. Kalb, R. D. Mailey, P. S. Millar, G. T. Minasian, A. L. Powell, E. M. Strong, and I. A. Yost.

The author acknowledges the co-operation of various members of the committee in supplying data and checking the manuscript.

[1] For all numbered references see list at end of report.

[†] In bulb designations the letter indicates the shape and the figure the maximum diameter in eighths of an inch.



Three sizes of photoenlarging lamps, from the largest to the smallest (left group); photoflood lamps of the regular and reflector types (lower right group). At the upper right are (left) a typical spot lamp and (right) a typical flood lamp of the projector type

sary long narrow sources. There has been no addition to the standardized line, but the "white", "moonlight blue", "straw", and "orange" finishes are now made with inside rather than outside coloring, because of greater ability to withstand weather conditions.

THREE-LIGHT LAMPS

A considerable number of sizes of low-wattage medium-base three-light lamps have been offered for sale. In certain sizes the differences between the various steps are too small to be entirely practical and the combination of low-efficiency small filaments does not make a lamp that has much economic justification. Their novelty has given them a certain amount of popularity, however.

To meet the demand for a light source to provide higher levels of illumination from indirect portable luminaires in the home, a 200–300–500-watt *G*-40 bulb mogul-base three-light lamp has been made available.

REFLECTING PROCESSED LAMPS

For several years rather large quantities of lamps with a silver coating on the hemispherical bowl of the bulb have been used for indirect lighting. The next step along this line was to coat the side walls of the bulb with reflecting material and use the lamp itself without external reflector to direct the light where needed. For this purpose, at first standard shapes of bulbs were employed, but these obviously were not designed to produce desirable distributions of light, so special filament mountings and bulbs of suitable contours were a logical step. Recently several new designs have appeared.

Filaments of 150- and 300-watt ratings are mounted in bulbs 5 inches in diameter by $6^1/_2$ inches over-all with part of the inner surfaces given a special process mirrored finish of aluminum. These are available in two light distributions known as "spot" and "flood." The former is more concentrated and the latter of wider spread. This construction gives the following candle power readings at the peak of the beam:

300-watt spot	16,000	150-watt spot	7,000
300-watt flood	3,000	150-watt flood	1,200

The reflecting lamps just discussed have bulbs of ordinary glass and must be protected from the weather, but some new lamps known as projector lamps are made of heat-resisting glass. In these the bulb is made in two parts, the cover being fused to the bulb after the high-efficiency concentrated filament has been positioned. Two types of cover plates are used, one to give a flood and the other a spot distribution. In the 150-watt size the flood type gives a maximum candle power of 3,500 and the spot type 10,500.

Tubular-bulb lamps of various sizes with half of the bulb having a reflecting coating are available for showcases and other places where space is limited.

DRYING LAMP

In many industrial processes radiant energy has been found to be most effective for drying purposes. Synthetic enamels and many lacquers can be dried in from 10 to 15 per cent of the time required by other methods. For this purpose a 250-watt *PS*-30 bulb tungsten-filament lamp has been developed. The filament is operated at an abnormally low temperature or efficiency ($7^1/_2$ lumens per watt), which avoids the production of unnecessary visible radiation and gives a very long lamp life. As a supplement there are on the market several types of concentrating reflectors for directing radiant energy to the surface

Eight sizes of standard photoflash lamps to be dried. Most of these are finished with electrolytic gold because this is efficient in reflecting the near infrared energy, permanent, and easily cleaned.

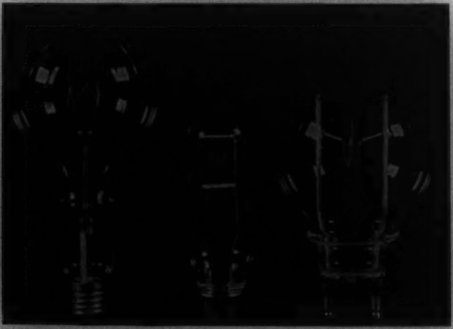
PROJECTION LAMPS

A rather startling advance has been made in this field with the development of 1,000- and 1,200-watt *T*-12 bulb biplane-filament lamps with a rated life of ten hours. The filaments and filling gas of these lamps incorporate improvements resulting in large increases in screen illumination and more uniform screen brightness. With the 1,000-watt lamp, for example, the lumen output is 32,000, and with a 16-millimeter motion-picture projector there is a gain of 50 per cent in light on the screen over lamps of previous design of the same wattage. In this field, also, improved optics have been introduced which make still further increases in screen brightness over that obtained with old style lenses and the same lamps.

With projecting lamps it is often necessary to prevent the light from escaping upward, and heretofore small metal caps have been used to slip over the ends of the tubular bulbs. Now the *T*-12 bulb 750-, 1,000-, and 1,200-watt projection lamps are regularly supplied with opaque end coatings.

An interesting medium-size projection lamp is the 300-watt *T*-8$^1/_2$ bulb lamp. This has a high-efficiency coiled-coil filament and a single-contact prefocused base. Being only 1$^3/_8$ inches in diameter and 4$^1/_8$ inches long it enables a source of 300 watts to be placed very close to the condensing lens and increases the amount of light entering the optical system of 8-millimeter motion-picture projectors.

During the past two or three years a considerable number of quite inexpensive toy projectors have been placed on the market. These are far from optically perfect, but they require brilliant concentrated light sources of decidedly low cost. For this purpose there has been standardized a line of several sizes and types of toy-projector lamps which retail at very low figures.



Left to right: old style 1,000-watt PS52-bulb lamp; 1,000-watt T24-bulb medium bipost lamp; and a mogul bipost lamp for projection service

BIPOST BASE LAMPS

The mogul bipost construction has become the accepted design for new types of high-current lamps. The medium bipost construction has been applied to the *T*-20 bulb 500-watt and the *T*-24 bulb 750- and 1,000-watt lamps for general lighting service, as well as to a considerable number of types of projection lamps.

A few of the projection lamps now available

The small over-all size made possible through the use of hard glass and the medium bipost construction has enabled designers to make commercial fixtures for high-wattage lamps of attractive proportions. A number of excellent designs along this line are on the market.

IMPORTANT CHANGES IN STANDARD LAMPS FOR GENERAL LIGHTING SERVICE

The standard life of 200- and 300-watt lamps has been reduced from 1,000 to 750 hours in line with production of light at minimum operating cost. The 300-watt lamp is now made in a shorter bulb with a medium screw base and 750-hour rated life. The 50- and 60-watt lamps are now standard in *A*-19 rather than *A*-21 bulbs.

In the last report mention was made of the application of the coiled-coil filament to projection lamps. This construction makes possible increased efficiency in certain sizes of the regular lamps. The use of this coiled-coil principle has been extended first to the 60-watt size and here a 10-per cent increase in light output resulted. The uncoiled wire from such a lamp is 20 inches long, and with double coiling this is compressed to only $^5/_8$ inch. Since the filament is so concentrated the cooling effect of the filling gas is minimized. This construction was next applied to the 50-watt lamp, then to the 100-watt size, and a program is under way to expand its use as manufacturing facilities permit.

FLASHLIGHT LAMPS

To permit accurate placement of flashlight filaments at the focus of reflectors, a simple type of prefocused base has been developed and applied to lamps of several sizes. Such accurate control, combined with die-cast reflectors, prevents distorted beams, provides more uniform and brighter spots of light, and materially increases the seeing range for general flashlight service.

SEALED AUTOMOBILE HEADLIGHTS

A most radical innovation in automobile headlights has taken place. In the past a typical assembly consisted of a plated parabolic spun reflector, an adjustable socket, a refracting cover glass or lens, and the necessary supports and housing. For accurate light control it was necessary to maintain three elements—the lamp, reflector, and lens—in exactly their proper relative positions. Even with rigid assemblies and careful workmanship, this was difficult because of the vibration and shock incidental to car operation. When these elements were out of optical adjustment a distorted and glaring beam resulted. In order to replace the lamp, it was necessary that the lens or cover glass be removable, and, in spite of attempts properly to gasket the joint, dirt and moisture accumulated on lamp bulb, reflecting surface, and cover plate. This accumulation materially reduced the light output.

"Sealed beam" automobile headlamp

Automobile manufacturers realize that with increased speeds safety in night driving required good headlighting and have been anxious to find some way of overcoming the two major difficulties just mentioned, produce something in which the human element of adjustment and maintenance was minimized, and obtain higher beam candle power. Work along this line has been proceeding for several years and has resulted in the development of two types of "sealed beam" headlamps, essentially the same in principle but different in structural details. These are entirely interchangeable, standard as to dimensions, and have the same light output and beam pattern. In one type there is a plated spun metal reflector to which a conventional-type two-filament bulb is soldered with the filaments in their correct positions. The lamp has three contact lugs so arranged that it cannot be inserted incorrectly in the receptacle. Across the mouth of the reflector is hermetically sealed a refracting-type cover glass. The maximum diameter is seven inches and the over-all length or thickness five inches.

The other type of sealed-beam lamp is similar to the projector spot and flood lamps in general construction features. The lamp bulb itself (Mazda lamp number 4030) is the complete unit. The shape is known as the *PAR*-56. Essentially it consists of an accurately designed pressed hard-glass parabolic section with aluminized coating on the inner surface; a refracting cover plate is welded to the back half of the lamp. In it are mounted two 6–8-volt filaments: one taking 40 watts is positioned for the so-called country beam; the other consuming 30 watts is positioned to produce a lower and sidewise-directed traffic beam.

Practically all the 1940 model cars have this new sealed-beam headlamp. An ingenious mounting arrangement has been designed and a standardized and universal switching arrangement for the two beams will be found. Since the new country beam is more powerful than previous types of "high" beam, there will be a campaign of education to make sure that operators switch to the traffic beam when meeting oncoming cars. It is anticipated that this radical development will be a tremendous factor in safe night driving.

Gaseous-Conduction Lamps

Continued research and development has made possible quite a number of new types of these lamps. The high-intensity mercury-arc lamp line, of which three sizes were mentioned in the previous report, namely, 400-watt (type *A-H*1), 250-watt (type *A-H*2), and 85-watt (type *A-H*3), now has in addition a 100-watt lamp (type *A-H*4), which emits 3,500 lumens, has a rated life of 1,000 hours, is made in a *T*-10 bulb and provides a low-wattage small bright source. The 250-watt size is also made with a smaller arc stream. This is known as the type *A-H*5, emits 10,000 lumens, has a rated life of 1,000 hours, and is a medium-wattage small bright source useful for floodlighting, and other purposes. Details of the theory and construction of these new lamps have been published in ELECTRICAL ENGINEERING.[2,3]

The water-cooled lamp has now been placed in production and is finding numerous and interesting applications. It is designed to operate at 1,000 watts and emit 65,000 lumens. The lamp itself is a small quartz tube with an arc stream $1^1/_2$ millimeters wide by approximately one inch long. This tube is placed in an outer jacket through which a flow of water of approximately three quarts per minute is necessary. Some special jackets have been made in which three lamps are placed side by side in one container. A rather special control system is necessary to make sure that the lamp will not be lighted before the water is flowing properly, that the water will be turned off if the lamp or power fails, and, further, that no voltage is applied in case of lamp failure. This lamp, known as type *A-H*6, is proving most useful in photoengraving, contact printing, high-power enlarging, copy-board illu-

A photoengraving unit employing the 1,000-watt A-H6 water-cooled high-intensity mercury-arc lamp

mination, oscillograph lighting, and other fields where an extremely brilliant and concentrated light source is required.

In Europe the 400-watt hot-cathode mercury lamp with a certain amount of cadmium added is on the market, fitted with an exterior envelope or bulb, the inner surface of which is covered with fluorescent material. This combination produces a whiter light at no loss in efficiency.

The standard low-pressure mercury-vapor lamp (Cooper-Hewitt) has been provided with an improved circuit which enables the complete unit to produce the same light output with a 22 per cent reduction in power.

Fluorescent Lamps

The last report mentioned that phosphors were being applied to the high-voltage cold-cathode type of gaseous-conduction lamp and that work was under way toward the production of standardized replaceable lamps for operation on commercial voltages incorporating the fluorescent principle. This is now an accomplished fact and is one of the most important innovations in recent years.

Lamps are now standard in 18-, 24-, 36-, and 48-inch sizes, which have a uniform rating of 10 watts per foot. In brief, an arc stream of low current density passes through mercury vapor to which a small amount of argon has been added for ease in starting. A slight amount of visible radiation (three to four lumens per watt) of the characteristic mercury color is generated, but this is accompanied by a considerable amount of radiation at 2,537 angstrom units. This ultraviolet radiation impinges on phosphors coated on the inside of the tube and is transformed into visible radiation at surprisingly high efficiencies in most colors.

One of the most outstanding features of this development has been the production of new types of phosphors which have proved very effective. There are now standard phosphors radiating green, pink, and blue light. By mixing these a white light very closely approximating, 3,500-degree-Kelvin black-body radiation can be produced. Another mixture gives an artificial daylight good enough for most purposes equivalent to that of a black body at 6,500 degrees Kelvin. If the tube coated with pink phosphor has also a layer of red lacquer, through selective absorption a red light is produced. Similarly, if the white tube has a coating of yellow lacquer, a golden light results. Thus seven colors are on the market.

Efficiencies vary somewhat, depending on the tube dimensions and color, but are of the following order:

White	35 to 47 lumens per watt
Daylight	30 to 40 lumens per watt
Blue	21 to 26 lumens per watt
Green	60 to 75 lumens per watt
Pink	20 to 25 lumens per watt
Gold	25 to 31 lumens per watt
Red	3 to 4 lumens per watt

At each end of the tube is a small coiled coated electrode. In operation these electrodes are first heated and when the electron emission reaches the proper point, the arc is struck and the electrodes are de-energized.

Since these are essentially arc lamps, every lamp requires some device in series with it to act as a ballast. Choke coils and small capacitors are used for this purpose. The ballast and a switching arrangement for energizing and turning off the electrodes are combined in auxiliary devices. These are of several types and sizes and in certain forms the controls for two lamps are included in one casing. Work is still under way on auxiliaries, and each month or two sees the introduction of new designs.

The tube or lamp has a cap at each end on which are placed two small pin contacts across which the electrodes are connected. A special lampholder is required. Space does not permit a complete discussion of the operating characteristics, of the factors that influence lamp performance, and of the specialized applications of this new illuminant. Some of these features have been described in previous articles and papers.[4–6]

The principle of fluorescence has also been applied to the standard low-pressure (Cooper-Hewitt) mercury-arc lamp. Here a rectifying type of a-c operation is used and a high-efficiency fluorescent material coated on the inside of a 52-inch tube. The lamp and auxiliary consume 100 watts and produce 5,000 lumens. Although the color of the light is similar to that of the Cooper-Hewitt lamp, the fluorescence adds a considerable amount of red and color rendition is decidedly improved, although no claim is made for white or daylight color quality. This lamp finds particular use for high-level industrial illumination with units mounted relatively low.

Ultraviolet Sources

In the sunlamp class one lamp has been developed known as the *S*-4. This is the same as the 100-watt *A*-*H*4 lamp discussed under "Gaseous-Conduction Lamps" except that it is fitted with an *A*-21 bulb of special transmitting glass. It has a somewhat greater output of ultraviolet radiation in the anti-rickitic region than the *S*-1 lamp and consumes only one-quarter the energy. The fixtures for the *S*-4 sunlamp are smaller, lighter, and easier to handle.

In the germicidal type, the "Sterilamp,"[7] a high-voltage cold-cathode type, is now made in 10-, 20-, and 30-inch sizes with ratings from about 10 to 20 watts. The following additional units have been made available:

Watts	Bulb	Base	Necessary Auxiliary	Life (Hours)	Microwatts Per Sq Cm of 2,537 A Radiation at One Meter
3	*T*-4	Radio type	Separate reactor	1,000	3–4
5	*T*-10	Medium screw	None required	1,500	1
15	*T*-8	Fluorescent	Same as for 15-watt fluorescent lamp	1,500	15–20
5	*T*-6½	Candelabra screw	Separate resistor	4,000	0.5
16	*T*-4	2-pin special	Separate reactor	1,500	15–20

These various germicidal tubes are finding considerable application for destroying bacteria. They have been experimentally installed in air ducts to kill air-borne bacteria; they are being used as a preventative to the spread of disease in hospitals, and for food preservation by various industries. Sanitization of drinking glasses and sterile storage of previously sterilized utensils are applications for these lamps which are becoming more popular every day. The relatively small size of some of the new tubes and simple control devices make them suitable for installation in places where space is limited.

A very useful new source for producing ultraviolet radiation for fluorescent and phosphorescent purposes is a result of modification and adaptation of the 100-watt type *A-H*4 lamp. This is made with a *T*-16 bulb of natural red-purple glass and emits a considerable amount of radiation of the type required for producing fluorescence, at the same time screening out most of the visible radiation. It is known as the type *B-H*4 lamp.

The Uviarc, a powerful source of ultraviolet radiation for industrial purposes, has been adapted for a-c operation. An entirely new line of these lamps with oxide electrodes and a limited amount of mercury has been introduced.

Carbon Arcs

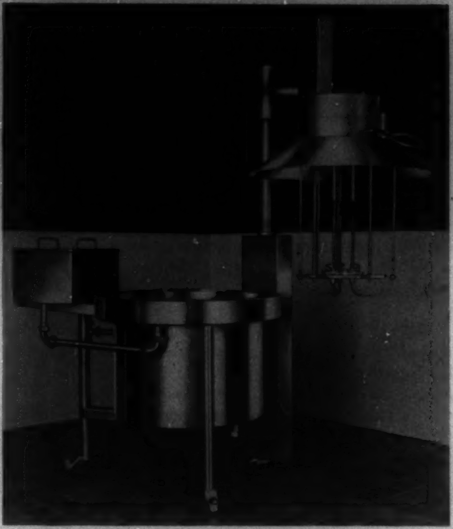
An improvement in carbon arc lighting for the motion-picture studios has been effected since the previous report of this committee through the development of a broadside lamp with motor-driven carbon-feeding mechanism. This development gives improved steadiness of light and a much lower sound level than lamps with solenoid-operated feed mechanisms.

A new super high-intensity carbon, 11 millimeters in diameter, provides an intrinsic brilliancy of 1,200 candles per square millimeter at an arc current of 135 amperes.

The development of carbon arc lamps for 16-millimeter motion-picture projection is extending the scope of the 16-millimeter film in educational and commercial fields, permitting the projection of a brilliant, sharply defined image on a much larger screen than has heretofore been practicable.

Three ultraviolet lamps of the germicidal type

The 3-phase carbon arc has been adapted to modern requirements and applied to a number of industrial uses. A 12-kw lamp, burning six carbons on a wye circuit, is being used for the vitamin-*D* activation of milk. For purposes of illumination this lamp provides a light source of one million lumens. A one-kilowatt, three-carbon delta-connected lamp is used in a new accelerated-fading-test unit. This lamp, equipped with carbons giving a spectrum similar to sunlight, is also used for illumination on applications requiring high-intensity light of daylight quality, free from the stroboscopic effects sometimes experienced with the single-phase arc.



A 12-kw arc lamp burning six carbons on a wye circuit being used for vitamin-D activation of milk

New Materials for Lighting

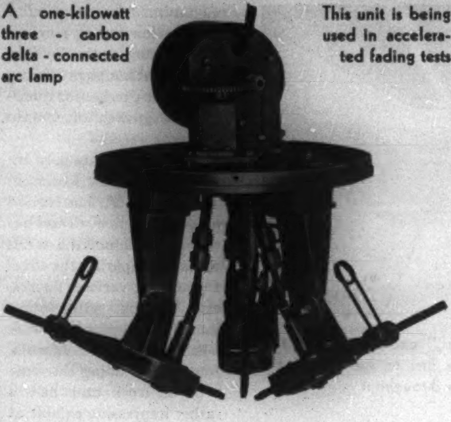
Glass blocks or bricks as structural elements have seen somewhat more extensive use during the past few years. Since these are translucent they offer opportunities for novel lighting effects, and quite a number of colorful schemes have been applied.

A new form of tempered glass has been introduced, and to this enamel of various colors is applied. This material is suitable for special effects in luminous store fronts and the like. In the same field different forms of weather-resisting metals lend themselves to interesting design in co-ordination with light and color. Mat and polished finishes, as well as porcelain-enameled corrugated metal are available to the designer.

Under normal conditions it is difficult to control the light reflected from a ceiling, for with plaster, soundproofing materials, and other coverings diffuse reflections result. One manufacturer of metal ceilings has placed on the market sheets so formed that controlled or regular reflection results. This is known under the trade name of Parab-O-Lume.

A colorless transparent plastic known as Lucite has found certain interesting applications. This material has the property of retaining a beam of light through in-

A one-kilowatt three - carbon delta - connected arc lamp



This unit is being used in accelerated fading tests

ternal reflections in much the same manner as a quartz rod. It has been applied to curved dental and surgical lighting devices where the beam is bent around the corner to illuminate some cavity.

Notable Lighting Installations

During the period under consideration there has been relatively little new building, but considerable revamping and modernization of existing structures. Practically all the leading shops on Fifth Avenue, New York, State Street, Chicago, and similar merchandising centers have installed unique and effective up-to-date lighting within the last few years. Many public rooms in hotels, restaurants, night clubs, and cafes are completely changed in appearance, and some of the most ingenious lighting to be found anywhere may be noted in this class of service.

It is impossible to tabulate the number of larger department stores that have discarded old systems and installed illumination schemes to take advantage of the most recent developments. As representative of this field we might mention: Gimbels, New York, N. Y.; Marshall Field, Chicago, Ill.; Kauffman's, Pittsburgh, Pa.; J. L. Hudson, Detroit, Mich.; Orecks, Duluth, Minn.; Z. C. M. I., Salt Lake City, Utah; Saks, Los Angeles, Calif.; Roos Brothers, San Francisco, Calif.; T. Eaton Company, Toronto, Ontario, Canada.

Remarkable advances have been made in illumination of banking institutions, and both the Los Angeles and Toronto stock exchanges have been completely relighted. The new service building of the Detroit Edison Company is an example of the application of many new principles of illumination, and the main office building of the Commonwealth Edison Company has an entirely new system.

Details of new and novel lighting installations are discussed in each issue of the Illuminating Engineering Society *Transactions* under a section conducted by the society's committee on the co-ordination of light and architecture. Those desiring to keep in touch with the most modern practice should refer to that publication.

There have been a number of international expositions or world's fairs, and, of course, in these the latest developments in lighting are always incorporated. Details of the Texas Centennial,[8] Great Lakes,[9] Paris,[10] and Golden Gate,[11] expositions have been reported in ELECTRICAL ENGINEERING and in other publications.

A manuscript describing and giving technical details regarding the lighting installation at the New York World's Fair 1939 is under preparation and is scheduled for publication in ELECTRICAL ENGINEERING when completed.

Lighting Instruments

Not long ago the rather cumbersome bar photometer with grease-spot screen was the only light-measuring device. With the development of the art of illumination the need for additional measuring instruments has grown apace, and each period has seen new types made available.

One rather interesting device, first developed in England, has been introduced in the United States, known as a light selection recorder. The observer, or subject, has a means of varying the illumination level on a test object and eventually selecting the amount of illumination he prefers. At this point he presses a button and on a printed scale is indicated the result of his choice.

With the growing appreciation of the importance of brightness measurements, some special meters have been developed for this purpose. A rather expensive and accurate type is known as the Luckiesh-Taylor brightness meter. A less expensive and more simple instrument, known as a model *L-H*, was developed by Luckiesh and Holladay.

Baumgartner has developed a light-cell reflectometer[12] and a light-cell distribution photometer. This latter device enables one to obtain a candle-power distribution curve in an extremely small fraction of the time required by the older method.

The widespread use of photoflash lamps has made it necessary to find some means of checking the setting of camera shutters in relation to the peak of light output. For this purpose a rather simple device known as the "synchrograph" was introduced. Another instrument along this line is known as a "flashograph," which traces

Brightness meter in use

on a moving film the performance of photoflash lamps. The lamp is flashed in a small sphere which has a photoelectric cell mounted on it. The amplified output of the cell is applied across a small Rochelle-salt crystal oscilloscope. The deformation of the crystal in reflecting a beam of light across the aperture of a drum traces the candlepower-time relation on film.

With the development of the ultraviolet lamp of the germicidal type (Sterilamp) the need arose for an instrument that would provide an exact quantitative measurement of the abiotic radiation from these lamps. The instrument developed to meet this need is an ultraviolet meter embodying a tantalum photoelectric cell, which has a wave-length response to ultraviolet radiation similar to the lethal action of these radiations upon bacteria. With the aid of this device, it has been possible to determine the abiotic energy necessary to kill any chosen micro-organism, and sterilizing installations may be planned with an exactness approaching that of the normal lighting installation.

Transportation Lighting

Real progress has been made in this field. Some of the tendencies have previously been reported.[13] New cars and busses, in general, are quite up-to-date from the lighting standpoint, and much work has been done in revamping and modernizing old vehicles.

With the coming of the fluorescent lamp the railroad engineers were among the first to consider its use. Since these lamps require alternating current for most efficient operation, the first step was the development of a vibrator inverter for operation on the storage-battery circuits. This device has worked out well in service. In some cases a small motor alternator set is used. The New York Central Railroad was the first to put in operation a fluorescent-lighted car. The Lehigh Valley Railroad's remodeled express train known as the "John Wilkes" has the honor of being first lighted by fluorescent lamps throughout.

Interior of the "John Wilkes," express train of the Lehigh Valley Railroad, the first to be lighted by fluorescent lamps throughout

Light in Horticulture

There is considerable interest on the part of various agricultural experimental stations in growing plants entirely under artificial light for the purpose of eliminating variables in order to study the effect of different chemicals, both for nutrient solutions and soil growth.

At Cornell University, Ithaca, N. Y., there is a room equipped with 24 1,000-watt lamps and a water filter, as well as humidity control. Ohio State University, Columbus, has a similar installation and is now experimenting with daylight fluorescent lamps producing 1,500 foot-candles for studying the growth of tomato plants.

The Boyce Thompson Institute for Plant Research, Yonkers, N. Y., has carried on continuous work and has recently conducted a series of tests comparing the effectiveness of various fluorescent lamps with other sources for plant growth. The University of California, Berkeley, is doing the same type of work and had a rather impressive exhibit at the Golden Gate Exposition during the 1939 season.

The color value of the daylight fluorescent lamp is apparently more suitable than that of filament lamps for stimulating plant growth. It gives much less radiant heat per foot-candle, and there is every indication that it will be an important factor in this field.

A notable installation of carbon-arc lamps for stimulating plant growth has been made at the field station of the United States Department of Agriculture, Beltsville, Md.

Sports Lighting

All the American Association baseball fields are now lighted for night playing and the "big" leagues are gradually recognizing the fact that night games pay well. Ebbets Field in Brooklyn, N. Y., has installed a total of 615 1,500-watt incandescent floodlights, and the Cleveland Municipal Stadium has now 712 units of the same size.

Show-Window Lighting

More than two decades ago the idea was promulgated that the show window was a miniature stage and that all the effects used on the latter would find application for the window display. It finally appears that the more progressive merchants are appreciating the logic of this approach. In the more artistic type of window spot lamps equipped with color mediums, flood effects, colored illumination of background, and combinations of all these are being applied with splendid results.

Street and Highway Lighting

Each year shows a growing public appreciation of the advantage of highway safety lighting even if one considers only the dollars and cents involved. New tests constantly show that the cost of this lighting is soon offset by decrease in accidents. In several states modernization plans are under way; in certain instances the installations are owned by the state. Many of the important cities have shown marked improvement.

There have been a number of new forms of street luminaires, most of which incorporate efficient Alzak reflectors. A rather novel feature in one type is the reflector spun onto the globe providing a weatherproof seal and greatly reducing glassware breakage.

Sodium lighting with its distinctive color has proved useful as a caution signal for safety-island beacons, as well as for especially dangerous intersections. The two new large bridges in California, the Golden Gate and the San Francisco-Oakland, as well as the Blue Water Bridge over the Saint Clair River between Michigan and Canada and the new Main Avenue Bridge in Cleveland, Ohio, are all lighted by the sodium system. This efficient light has also proved very acceptable for underpass and tunnel lighting, notable installations being the Two Rock Tunnel on the Columbia River Highway in Washington, the Liberty Tunnel in Pittsburgh, Pa., the Stockton Street Tunnel, San Francisco, and the McCallie Avenue Tunnel, Chattanooga, Tenn.

Aviation Lighting

Improved efficiency in the design of conventional types of aviation lighting equipment and the introduction of new types of lights have combined to make the past four years a period of important progress. The trend in beacons has been a return to the 24-inch size but the design has been "streamlined." The trunnion arms have been eliminated, reducing the area exposed to wind and the risk that ice and snow may interfere with smooth rotation. The base has been redesigned to afford better access to the mechanism for maintenance. A new lamp changer eliminates the shadow of the reserve lamp from the beam. Another form of this beacon is also available in which the drum has been replaced by a glass dome, the rotating parts thus being completely enclosed. To provide a beacon with more frequent flashes, an oscillating beacon has been developed. In this unit a lamp moves up and down on the axis of a cylindrical Fresnel lens giving 80 flashes per minute. This beacon also has more candle power at high angles than the 24- or 36-inch beacons.

Stockton Street Tunnel, San Francisco, Calif., lighted by 10,000-lumen sodium-vapor units

An experimental boundary-light circuit in which the lamps are fed by a 550-volt multiple circuit through individual transformers has been installed at Washington (D. C.) Airport. The circuit is less expensive than a series circuit and the voltage drop is much less than with an ordinary multiple circuit. It is well adapted for use on fields that do not have sufficient night traffic to warrant the outlay required for a series circuit.

Floodlighting is being designed with greater attention to the avoidance of glare. This has led to the development of an improved 90-degree unit employing four 1,500-watt lamps each in a separate Fresnel lens. The four separate sources give insurance against a sudden interruption of the illumination by the burning out of a lamp.

The development of the approach-and-contact-light system has largely taken place in the last four years. This system was originally designed to supplement radio aids in fog, but its use in good weather has found much favor. The approach lights are located outside the landing area and are accordingly red. Neon lamps approxi-

Shibe Park, home field of the Philadelphia (Pa.) baseball club of the American League, illuminated by 780 1,500-watt floodlights mounted high above the field on eight towers, one of which is shown at the right

Grill room of a New York, N. Y., hotel with fluorescent units recessed in the columns

mately six feet in length, with suitable parabolic reflectors, give an intensity of 1,000 candles and, by their elongated shape, establish a horizontal plane of reference to guide pilots in approaching the runway. The contact lights are arranged along the two sides of a runway to show its location and indicate the ground level. These units project less than two inches above the runway and are available in two types. Heavy-duty units are used on runways that are in line with approach-light systems or furnished with radio aids for instrument landings. Normal-duty units are used on other runways. Contact lights are lighted on only one runway at a time. The approach-and-contact-light system, in addition to being one of the most satisfactory aids for night landings, is also the most effective means available for giving an airport a distinctive appearance at night; this is a great aid to a pilot looking for an airport with which he is not familiar.

There has been marked progress in the development of traffic-control lights. Lights visible only along the runways are being installed at several airports to control taxiing movements and take-offs. For controlling landings, 90-foot arrows composed of red and green marker lights are being installed at the ends of the runways. A green arrow indicates that landings may be made from the end of the runway so marked. A red arrow shows the landing end of a runway that must not be used at the time.

The growing overseas air traffic is necessitating equipment for use as seaplane-channel marker lights. Some very interesting experiments have been conducted with battery-operated coiled-tube fluorescent lamps mounted on resilient rubber floats to meet this need. The Civil Aeronautics Authority expects to establish specifications for seaplane-channel lights when these experiments have yielded sufficient data.

Electrical Advertising

The most novel feature in the incandescent-lamp type of sign is noted in the further development of the "motion picture" type of display. In such a sign moving images from a motion-picture projector are thrown upon a screen made up of photoelectric cells which, in turn, light up a huge bank of incandescent lamps in accord with the light and shade of the projected image.

In the gaseous-conductor type of display the familiar orange-red of the neon and the blue of the mercury have become so common that in many cases the colors lose their appeal and attracting power, and the variety of effects possible through fluorescent lamps are indeed welcome to this industry. It is reported that a very high proportion of all new work incorporates fluorescent tubing.

In the smaller type of displays many very unique features have been incorporated. One popular and inexpensive form uses letters or emblems made up of glass tubing in which volatile liquid is placed. There is a reservoir or small bulb at the bottom. The heat from concealed lamps causes a continuous moving bubble effect and the fluid itself is luminous from the light emitted by the lamps.

Another type of sign has a message formed by a thin wire which serves as a negative electrode for an electric discharge in a helium-filled tube. Still another takes advantage of the phenomena of high-frequency discharge. Changeable letters are filled with neon or other gases. An oscillator is placed in the base of the sign or nearby. There is no electrical connection, yet the letters glow with a fair luminosity. Standard colored low-voltage fluorescent lamps have been effectively applied to a number of signs based on the edge-glow and transparent-mirror principles.

Lighting Standards

The Illuminating Engineering Society as the guiding body has continuously conducted researches into various fields of practice. From the industrial angle the special requirements of different processes have been studied and these findings have been reported from time to time. The philosophy behind this procedure has been discussed in ELECTRICAL ENGINEERING[14] and in IES *Transactions*.[15]

Codes applying to airport,[16] highway,[17] and schoolroom[18] lighting have also been published.

Polarized Light

Polarized light is as old as time itself, but has never been a very useful tool for the lighting engineer because of the expense and complication in producing it. Its properties are well known to all who have studied physics, and obviously if it could be made available simply, many valuable and practical effects would result. For several years investigators have been trying to produce a synthetic medium which when placed before a light source would act as a polarizer. Such a material (known as Polaroid) is now available in sheets of considerable size.[19] To the unaided eye it appears as a sheet of thin gray or neutral-colored gelatin filter. Structurally, however, in this sheet are innumerable small microscopic slivers, practically all pointed in one direction. When two sheets of Polaroid are placed with these needle-like particles parallel, maximum light transmission results. When placed at right angles to this position, practically all the light is cut off.

Polaroid mounted between pieces of protecting glass has found rather wide use in sun spectacles. Placed before the openings of reflectors directing light on paintings it provides a means of reducing specular surface reflections to a minimum. Desk and reading lamps have been equipped to furnish polarized light. Beautiful decorative effects for the theater and advertising purposes result from the action of polarized light on cellophane and similar materials.

One of the most interesting fields for the application of the polarizing principles is in connection with automobile headlights. Here the proposed scheme polarizes the light from the headlamp in a 45-degree angle and places on the windshield an analyzer at the same angle. Thus there is minimum reduction in visibility of the beam from one's own headlights, yet the light from oncoming headlights being at right angles to the analyzer, is scarcely visible.

To date, however, many practical difficulties have prevented the adoption of such a scheme. For the idea to be effective, it would be necessary to have all cars similarly equipped. Under ideal conditions the efficiency of such a lighting system would be in the order of 25 per cent. Under practical conditions such as exist at the present time, however, this figure is considerably less. Hence for the same brightness of objects to be seen, generator capacities would need to be increased more than fourfold. The proposed system would tend to work additional hardships on the pedestrian and at the same time reduce the brightness of the street illuminated by standard overhead sources to at least one-half.

Fluorescent lighting in a New York, N. Y., fur shop

Colored background lighting by means of fluorescent lamps in the show window of a Fifth Avenue shop in New York, N. Y.; merchandise is lighted by reflector spot lamps

Lighting Control

The thermionic-tube control combined with saturable reactors has been improved in certain details. In the first stages of development it was necessary to have a reactor with a rating approximately equal to that of the load to be delivered. Thus a reactor rated for 5,000 watts would not function with a load of one kilowatt. Now, however, reactors are available that will operate over the following load ratios: 1–2, 2–1, 4–1, 10–1, and 30–1.

When this system was first introduced, it was necessary to connect reactors in cascade, which meant that different sections of an installation being thrown on the line would come up to full brightness at slightly different intervals. Now reactors are operated in parallel eliminating this distracting feature.

There has been announced a four-circuit thyratron reactor mounted on a single chassis for mobile light control.

Photoelectric relays for lighting control have been improved and a new circuit used for the control of street and floodlighting. Less equipment and smaller space is required. The new relay is much more sensitive and turn-off and turn-on values can be very close together. Automatic control for the schoolroom has long been desired, for the teacher with her mind on a multitude of other things very often neglects the matter. Such a scheme is not practical, however, unless a decidedly inexpensive and simple photoelectric device is available. This is now the case.

Meeting of the International Commission on Illumination

The International Commission on Illumination, familiarly known to English-speaking people as the "ICI", to the French as "CIE", and to Germans as "IBK", convened for its tenth session in Scheveningen, Holland, June 11 to 20, 1939.

It drew an attendance of over 500 including 11 delegates and 9 guests from the United States. In addition to the 14 member countries, several others were represented, two other applications for membership being received.

From the American viewpoint, the session was probably one of the most interesting and productive of the ten sessions that has been held. Without neglecting standards and other basic questions, an increased amount of attention was devoted to the interchange of information and opinion on the late developments and trends in the art and science of illumination, ranging from laboratory investigation and field surveys to views as to future trends on lighting practice.

Reports covering 32 main topics were presented by 24 technical committees; the two United States secretariats submitted four of these reports. In addition to these, 34 papers by individual authors were presented for discussion, none of these being by American authors.

Among the fundamental questions taken up were the "new" candle, and the several topics arising out of the application of luminosity factors to photometry and colorimetry. Nearly all practical photometry throughout the world is now carried on by physical methods, even to the checking of visual standards.

Some additions were made to the English-French-German lighting vocabulary, which had been printed since the 1935 sessions. Arrangements were also made for the inclusion of equivalent terms in other languages in addition to Spanish and Italian.

Much information on the new electric discharge lamps was brought out as well as data on the recent developments of other illuminants. In the fields of illumination, street lighting, automobile lighting, aviation lighting, railway lighting, and school lighting, the United States Committee contributed information on a relatively extensive scale.

At the conclusion of the technical sessions, a program was adopted for the ensuing three years, 25 secretariats being allotted to the several national committees. In addition a plan was adopted for the presentation of individual papers at the 1942 sessions.

Officers were elected including Doctor Halbertsma of Holland as president and E. C. Crittenden (A'19, M'22) of the United States as one of the three vice-presidents. The invitation of the French committee to hold the 1942 Session in Paris was accepted, while an invitation from the Polish committee to hold an intermediate meeting of the aviation lighting committees in Warsaw was deferred for later action.

Now that Warsaw is in ruins and the great countries of Europe are too busy with destruction to give attention to co-operation on constructive effort, these plans presumably are canceled.

General

It is believed that the above data are a truly remarkable record of progress in an art in a very short space of time. It is impossible to give due credit to the many workers in the field of lighting. They are legion, and here and there without fanfare or publicity, without public recognition, these individuals advance the art here a little, there a little. The cumulative effects are of vast importance to the public. This work is often not sufficiently spectacular to receive much publicity, but it is none the less important and of a nature that is appropriate for engineers to recognize.

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An Armchair Spectator Conveyer-Guide

JAMES DUNLOP W. T. WHITE

Visitors to the General Motors "Futurama" at the 1939 New York World's Fair, an extensive scale model purporting to depict the America of tomorrow, were transported through the exhibit on a specially designed and constructed conveyer consisting of a continuous train of moving chairs almost one-third of a mile long. Loudspeakers provided each individual spectator with a running account of the changing scene throughout the tour.

As SUCCESSIVE world's fairs have grown in size and diversity, the exhibitors have built larger and more elaborate buildings, and the exhibits themselves have become more diversified and of more general interest. This trend is exemplified no better than at the 1939 New York and San Francisco fairs. What has proved to be one of the real hits of the New York fair is the "Futurama" exhibit in the General Motors Building (5,000,000 visitors during the 1939 season); it is said to be the largest scale model ever built, covering nearly 35,750 square feet and extending for almost one-third of a mile. It contains about 500,000 buildings, over 1,000,000 trees, and 50,000 scale model automobiles, 10,000 of which actually operate. Visitors are taken on a tour over a miniature cross section of America. They see mountains, valleys, and plains, cities, towns, and farming communities, rivers, lakes, and dams, and through it all run the proposed superhighways of the future with their traffic control towers, multidecked bridges and separate lanes for speeds up to 100 miles an hour. This exhibit cannot adequately be described; it must be seen. But the 140-ton 600-seat spectator conveyer, which has a capacity of about 30,000 passengers per exhibit day, and the sound system, "20 tons of voice," which replaces 150 private guides—one for every four passengers on the conveyer—are unique.

From figure 1, it may be seen that the conveyer is set up on an endless, circuitous track which has many radii varying from 9 to 98 feet with changing elevation reaching a maximum of 23 feet above the lowest point. There are

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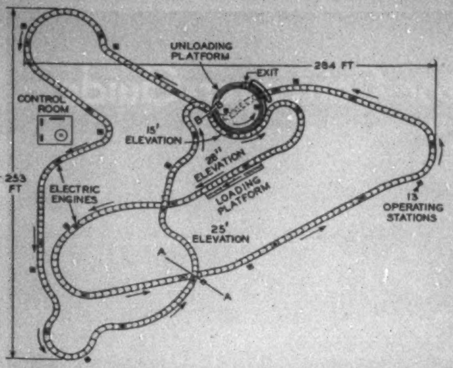

UNLOADING PLATFORM
284 FT
EXIT
CONTROL ROOM
15' ELEVATION
28" ELEVATION
LOADING PLATFORM
253 FT
ELECTRIC ENGINES
13 OPERATING STATIONS
25' ELEVATION
A
A
B
B

Figure 1. Plan diagram of conveyer in General Motors "Futurama" exhibit at the New York World's Fair

Length of conveyer—1,568 feet
Electric "engines"—23
Passenger capacity—600
Round-trip time—15 minutes
Passengers per hour—2,400
Crest of undulation—23 feet
Area covered—44,000 square feet

spiral sections of the track having an incline of one on six, with a radius of 18 feet.

The total length of the track is 1,568 feet. It consists of a channel-shaped center track which definitely fixes the path of the conveyer. The outer tracks are angle shapes having the flat surface horizontal to receive the wheels of the train.

Referring to figures 2 and 4, these three tracks are shown to be mounted on a structural trestle which extends throughout the entire path of the conveyer.

The conveyer consists of 322 platforms of sufficient width to carry a double chair and still leave ample passageway in front of the chairs as shown in figures 3 and 4. The surface of the platforms must be flush with each other and the space between them as they pass over the undulations must not vary enough to create a hazard.

The length of the platform is about five feet, one end being made concave and the other convex. At the concave end immediately beneath the surface is provided a channel track upon which rest small Micarta rollers mounted on pins, set radially to the center pin in its mating platform. The center pin has a soft-tired roller mounted on it which runs within the channel-shaped center track.

From figure 5, it may be noted that the platform is mounted on caster-type rollers placed on the bisective line of the chord between the center pins of adjoining platforms. This arrangement completely eliminates any tendency of scuffing or skidding of the rollers on the track. There is considerable warpage in the platform as it passes through the spiral track, but by having it supported on the tracks by only two wheels at one end and at the other end on wheels enclosed in the channel track of its mating platform, the surfaces of the platforms are kept flush with each other.

The chairs are mounted on three-point supports of deep sponge rubber so as not to limit the required warpage of the platform.

The platforms are connected by wishbone-shaped couplings designed to have rigidity in the horizontal direction only but to have flexibility in the vertical so as to accommodate themselves to the positions of the platforms at all times. The bearing at the "elbow" of the "wishbone" is mounted on the center pin of the platform, and the adjusting screws at the ends of the arms of the wishbone are fastened to a cross member of the mating platform.

This endless train of platforms must be made exactly

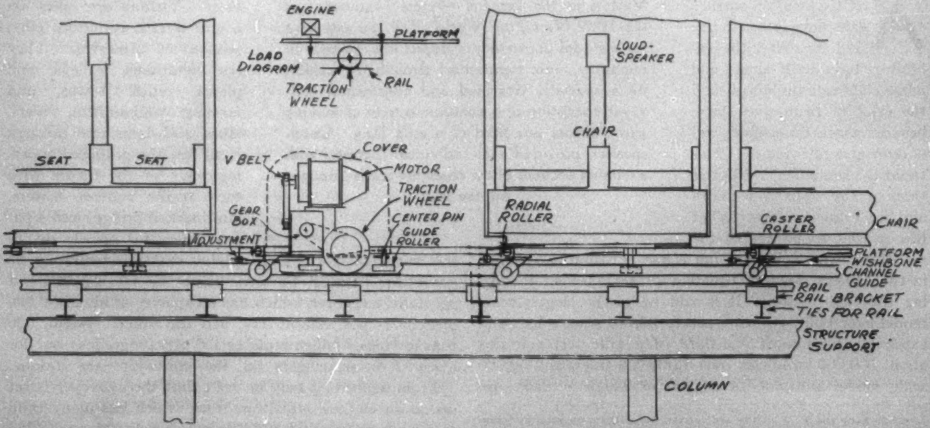

ENGINE
PLATFORM
LOAD DIAGRAM
RAIL
TRACTION WHEEL
LOUD-SPEAKER
CHAIR
SEAT
SEAT
V BELT
COVER
MOTOR
TRACTION WHEEL
GEAR BOX
CENTER PIN
GUIDE ROLLER
ADJUSTMENT
RADIAL ROLLER
CASTER ROLLER
CHAIR
PLATFORM
WISHBONE
CHANNEL GUIDE
RAIL
RAIL BRACKET
TIES FOR RAIL
STRUCTURE SUPPORT
COLUMN

Figure 2. Sketch showing design and loading diagram of conveyer "engine," and general arrangement of running gear

the same length as the tracks, which is accomplished through the adjusting screws at the ends of the wishbones as shown in figure 5. One turn of the nut on the screw between each car and the next would represent a change in the total length of the train of 30 inches. The problem of change of total length of the track measured in platform pitch due to the cordal action of the platform pitch passing round the many radii was solved by the arms of the wishbone being made slightly corrugated; this permits of slight lengthening or shortening of the train.

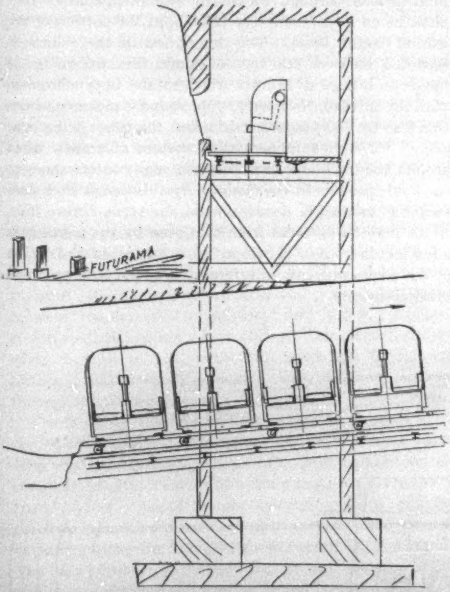


Figure 3. Sketch showing section at A-A of figure 1 where chairs at two different elevations are at right angles to each other

To drive the conveyer, 23 "engines" are furnished, one on every 14th platform. Each engine platform is provided with an opening in its center to permit the traction wheel of the engine reaching and resting on the bottom of the channel-shaped center track.

The engine consists of a two-horsepower compound-wound electric motor driving a rubber-tired traction wheel through a V belt, worm-gear reducer, and roller chain as shown in figure 2. This equipment is mounted on a sole plate which has one end attached to the center pin of the platform by a universal ball bearing. The other end has a roller fastened to it which lies in the horizontal position within the center guide track. The position of the rubber-tired traction driving wheel is exactly central between the roller on the center pin and the roller on the other end of the sole plate. Thus the traction roller is always in the theoretically correct position with respect to its travel throughout the entire path of the center track.

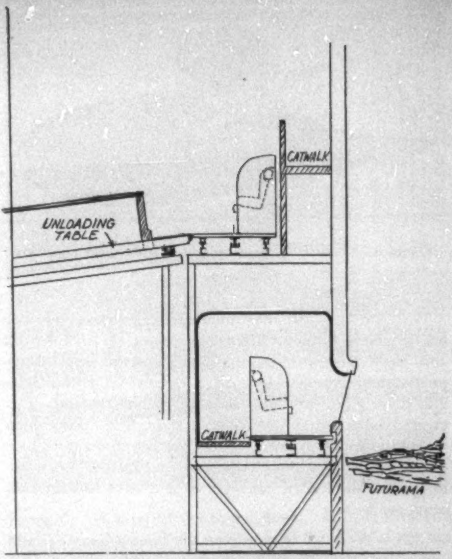


Figure 4. Sketch of conveyer at B-B of figure 1 showing chairs at different elevations facing and moving in opposite directions

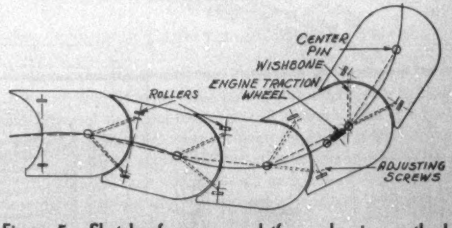


Figure 5. Sketch of conveyer platforms showing method of coupling the cars together

The load diagram at the top of figure 2 shows how the reaction of the weight of the engine and of the platforms is taken on the rubber-tired wheel, thus obtaining the necessary tractive force. Power is fed to the 23 engines through a trolley system underneath the platforms, and the connection is made to each motor through a carbon-brush system which slides along the surface of the trolley wires. These trolley wires are made of an H section, having a smooth, flat surface on top. The control is of the variable-voltage type, power being supplied by a motor generator set.

Figure 6. Top of "engine" platform with cover removed

It should be noted that the available tractive force for one engine is to be multiplied by 23 for the entire train and, since the conveyer is endless, power is applied approximately every 68 feet of its length. This multiple-unit drive gives the "lift" and the "push" that are of so great advantage in overcoming the difficulties which otherwise would be set up by the varying train resistance due to grades and track curvature and makes it possible to operate the loaded conveyer at a cost of less than 25 cents per hour.

Equally interesting is the fact that, as shown in figures 3 and 4, certain cars in the same endless train are moving, one directly over the other, in exactly opposite directions, while others travel at right angles to each other at the same time.

Sound System

Concealed in the center arm of each double chair is a loud-speaker through which the two occupants of that chair listen to a descriptive talk about the portion of the exhibit before them. The description of the exhibit is recorded on over 600 feet of sound film wound in 24 bands on a huge steel drum which rotates in synchronism with the spectator conveyer. The sound is picked up from this film by 150 photoelectric tubes, the tubes being connected through amplifiers to a system of trolley wires around the track and from these through contact shoes to the loud-speakers in the chairs. By this means each passenger is assured a description of the scene before him, which may be different from that seen by the passengers a few feet in front of or behind him. The acoustical design of the chairs prevents interference between loud-speakers in adjacent cars.

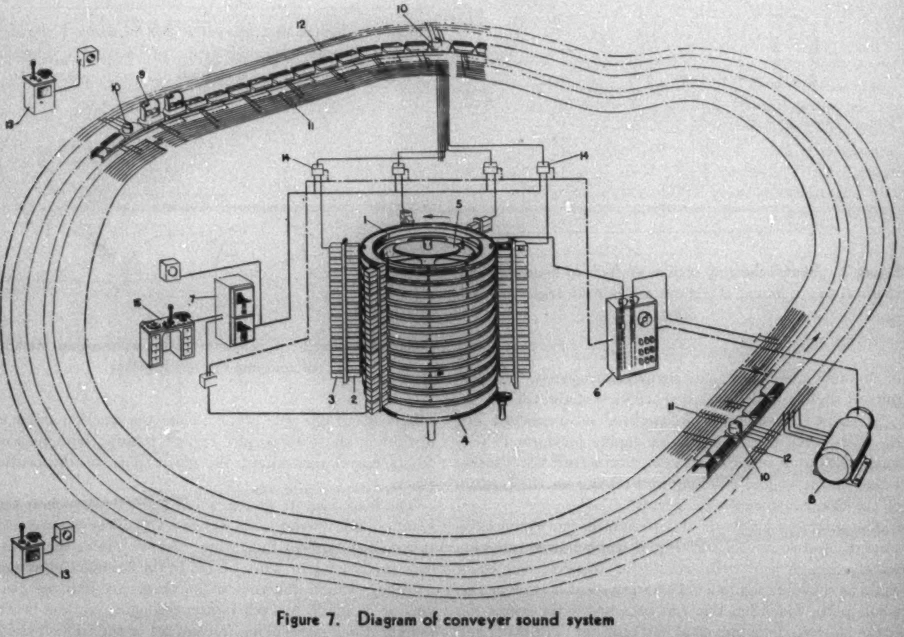


Figure 7. Diagram of conveyer sound system

1—Film-carrying drum
2—Scanning units
3—Amplifiers
4—Drive gear
5—Synchronizing cam and contactor
6—Synchronizer
7—Emergency amplifier equipment
8—Conveyer power generator
9—Spectator sound chairs
10—Motor cars
11—Sound trolley wires
12—Power trolley wires
13—Safety-officers' equipment
14—Emergency announcing relays
15—Control desk

The sound-film drum constitutes an amazing piece of precision construction for an apparatus so large. This drum is 8 feet in diameter and stands 12 feet high from a circular base housing the driving mechanism; it weighs more than seven tons. Since any variation from true in the movement of the film riding on the drum would result in sound distortion, the drum was constructed to deviate from a perfect circle by not more than 0.0008 inch at any point of its 27-foot circumference.

The drum and drive mechanism weigh about 20 tons and are supported by a mat of rubber resting on a heavy concrete foundation. This construction prevents any vibration from interfering with the photoelectric sound pickup system. To minimize expansions and contractions from temperature variations, the entire sound reproducing system is housed in a special air-conditioned room where the temperature never varies more than two degrees and where humidity is held within five per cent of its specified value.

The trolley system is also unique. It was found that a satisfactory relationship between sound and scene could be maintained for each spectator if a separate voice circuit was supplied to each pair of cars. This would appear to mean 150 different circuits and trolley wires, but space between the car rails would admit only a few. Trolley-circuit sectionalization solved this problem; seven trolley wires, instead of 150, were laid down and these were broken, with insulating joints, into 68-foot sections throughout the whole tour.

The story for the first 68-foot section of the tour is recorded on one of the 24 loops of film. This record takes 40 seconds to reproduce, which is the time required for one complete revolution of the film drum and for a given car to travel 68 feet. One of the photoelectric pickups scanning this loop is associated with one of the seven trolley circuits extending along the first 68-foot section of the Futurama. The loud-speakers in the first pair of cars in each 68-foot section connect with this particular rail. Sliding contact is made through a silver-impregnated shoe beneath the car.

When the rotation of the drum is properly synchronized with the speed of the cars, this shoe first touches its trolley wire just as the story is commencing. As the story finishes, for that 68-foot section, the contactor shoe is carried to the next section of the same wire where the story is continued from a second loop of film. Similarly, all the remaining sections of trolley wire, fed from other film loops, tell consecutive parts of the story until the cars have completed one round trip.

In addition to this first scanner, six others are spaced at equal intervals around the loop of film, as previously mentioned. Each of these scanners connects with some one of the six remaining trolley circuits in each section of track. All 24 loops are so scanned by seven pickups. Obviously, the beginning of the story recorded on each loop arrives at each scanner progressively. By connecting each pair of cars in any one section with the proper trolley wire, sound matching the scene before that pair of cars will be projected to the spectator.

An eighth trolley wire, paralleling these seven, provides a common return path for all speech circuits. In addition, a short section of wire, slotted into approximately two-foot lengths, extends along the loading zone for synchronizing purposes.

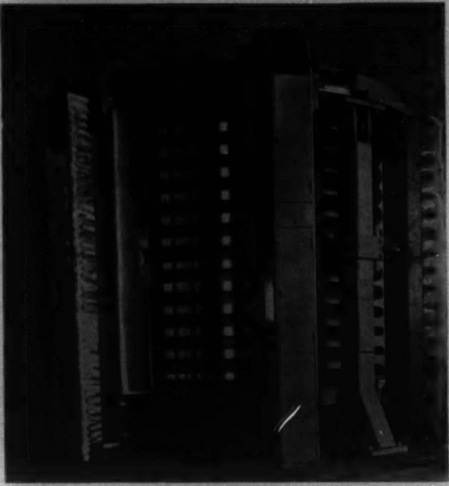


Figure 8. A view of the sound drum. A loop of sound film is wound around the periphery of the drum at the top and bottom of each of the 12 rings

Synchronizing Conveyer and Sound System

Since the sound for the Futurama is produced by a film-carrying drum rotated by synchronous motor at constant speed past photoelectric-cell pickups, this machine sets a pace that the conveyer must duplicate if the correct sound is to be reproduced on the proper loud-speaker. Synchronization is accomplished as follows: Two similar auxiliary devices are provided, one of which is made to move in exact relation to the movements of the sound machine while the other moves in the same relation to the movement of the conveyer. This is accomplished by the use of two motor-driven carriages one of which moves in response to impulses set up by the rotation of the sound drum, while the other in a similar way responds to the movement of the conveyer. Thirty-eight impulses drive the sound carriage the length of its travel, which corresponds to one revolution of the sound drum. Thirty-eight impulses also drive the conveyer carriage the length of its motion, which covers about 68 feet of conveyer travel. In this distance a given point on the conveyer travels past as much of the Futurama as can be described in one rotation of the sound drum.

The two motor-driven carriages are arranged with brushes contacting segments and cross connections such that when they move together no action occurs. If the conveyer carriage lags behind the sound carriage a relay picks up to increase the conveyer speed by raising the main generator voltage, and the opposite occurs when the conveyer carriage gets ahead of the sound carriage.

To start the conveyer and have it pull into step automatically the following sequence occurs: When the starting circuit is completed the conveyer starts at slow speed, about five feet per minute. The sound drum is rotating at a constant speed of 104 feet per minute. The two carriages are moving at proportional speeds, and after a few seconds the sound carriage approaches the position of the conveyer carriage. At a predetermined point before the sound carriage overtakes the conveyer carriage, corresponding to about eight feet of conveyer travel, the conveyer is accelerated to its full speed (104 feet per minute). While it is accelerating the sound carriage is overtaking the conveyer carriage and as the conveyer reaches full speed the two carriages are in the synchronized position. The automatic synchronizing circuits previously mentioned maintain this relation from this time on.

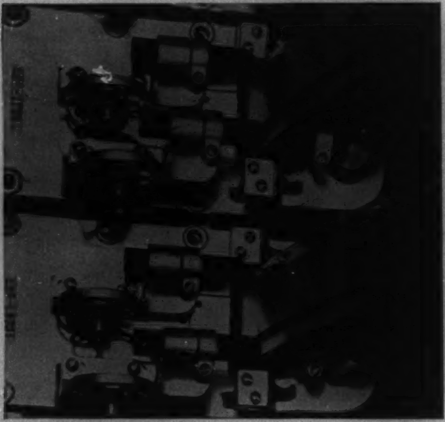


Figure 9. Close-up of photoelectric pickups which scan the sound films wound around the drum. Axial deviation of the film does not exceed 0.0004 inch

The conveyer itself runs through a soundproofed and air-conditioned tunnel with glass windows on the side faced by the passengers who thus get the effect of viewing the entire Futurama from a low-flying airplane. Directly behind the conveyer in the tunnel is a continuous catwalk with convenient exits to the building. In case of an emergency shutdown any passenger could easily walk not more than 20 feet over the interlocking platforms to one of the openings leading to the catwalk.

The conveyer system is controlled from a main control station located in the sound-system control room where a supervisor is continually on duty. Located around the track and connected to the main station are 13 other control stations each with an attendant on duty at all times. To start the conveyer each attendant must press his starting button which will light a lamp in the main control station. When all stations have given the starting signal the supervisor can then start the conveyer from the master control board. The stop button in any station, when pressed, will immediately stop the entire conveyer and is held in magnetically until released by the attendant.

Loading and Unloading Platforms

The loading platform is practically the equivalent of a horizontal electric stairway 40 feet long with horizontal treads which are level with the platform of the conveyer and travel at the same speed. It has comb plates at each end and on the outside has balustrading, together with a moving handrail. Passengers feed onto this loading platform just as they would enter an electric stairway and then step directly onto the platform of the conveyer and take their seats. If, for any reason, anyone should decide not to board the conveyer, he may simply proceed to the discharge end of the loading platform and step off.

The circular unloading platform is a metal ring approximately 32 feet in diameter inclined at an angle of five degrees. Its surface is covered with continuous aluminum cleats and its edge is made with a series of flats which accurately engage the edges of the conveyer platforms; the latter curve around part of the unloading platform so that several spectator platforms may be flush with the unloading platform at one time. A balustrade is provided continuously on the inside edge of the unloading platform and of course revolves with it. At the discharge where the conveyer swings away from the unloading platform, a similar but stationary balustrade with a moving handrail is provided parallel with the outer edge of the unloading platform together with a comb plate at the end. A passenger having completed the trip rises from his seat, steps onto the unloading platform which is at the same level as the conveyer platforms and moving in synchronism with them. Almost immediately he reaches the moving handrail, takes hold of it, and is conveyed down to the comb plate where he alights.

Credit for this remarkable exhibit is due in great measure to the vision and courage of William S. Knudsen, president of General Motors Corporation, the co-operation of D. C. McGuire, general manager of the General Motors Argonaut Realty Division, and the ability of Norman Bel Geddes, the designer, Albert Kahn, Inc., the architect, George Wittbold, the exhibit engineer on diorama, and the Turner Construction Company, the general contractors. Electrical Research Products, Inc., designed and (with the exception of the sound drum itself which was built by the Westinghouse Company) built the extremely intricate sound system. Westinghouse Electric Elevator Company furnished the spectator conveyer with its loading and unloading platforms, and the special devices that synchronize the conveyer and the sound system. James Dunlop, division engineer for the Westinghouse Electric Elevator Company, was responsible for the successful and unusual design of the complete spectator conveyer, and W. F. Eames handled the electrical equipment and designed the synchronizing devices.

The Human Science

C. T. WELLER
MEMBER AIEE

Like many other words in our language, "science" has more than one meaning. It may be defined as systematized knowledge in general and also as any branch thereof. When we think of the various branches of science, we are apt to stress those like astronomy or metallurgy that are inanimate, inorganic, impersonal. Occasionally, therefore, it is well to remember that there is another science, a very human one—anthropology—the science of man himself. As might be expected from the wide range of human activities, anthropology is a very broad subject and can be here outlined only in part. In so doing, that sword of Damocles, the possibility of error, which hangs over the head of every scientist, is acknowledged at the start.

Those who can remember back half a century may recall some of the theological controversies then current. I am told that one of them involved the question as to whether or not the Creator had limited himself in any way. One country preacher had very strong convictions on this question. He contended that not even the Almighty could create a two-year-old heifer in a day. He conceded that a heifer could be created that would resemble the two-year-old heifer in all respects except one; she would *not* be two years old. This proposition might be restated as gradual versus instantaneous growth. From a scientific standpoint, we seem to have no evidence of instantaneous growth, but we do have considerable evidence of gradual growth which it might be of interest to review.

Short-Term Growth

Everyone is familiar with the growth of a child. Doctor Steinmetz in his book on "Engineering Mathematics" pointed out that each child during its first years of life repeats the development of the race throughout the ages. While physical growth slows down toward maturity, mental growth continues. A few moments' introspection will doubtless evoke indulgent smiles as we recall how naïve we were only a few years ago. What has caused the changes noted? Equal increments of time and unequal increments of experience have somehow produced diverse results, and the chances are that today we are quite different mentally from what we were say a decade ago. Perhaps we have acquired a broader outlook, a firmer grasp on fundamentals, or a more effective discipline. Although somewhat uneven, this growth, like that of a child, by and large has been gradual. Yet what seems gradual when compared with the complete cycle of the individual becomes swift indeed when compared with the time elapsed since the beginning of life on the earth. Thus the individual cycle can be considered as short-term growth.

Long-Term Growth

What of man's long-term growth? For an excellent example of long-term growth, we turn to our good friend the horse. The first known ancestor of the horse was an animal about the size of an ordinary cat, having several toes on each foot. This ancient animal was so different from a modern horse that the relationship at first was not suspected. It required the discovery of intervening types of increasing size and decreasing number of toes finally to establish the relationship. In passing, it is interesting to note that our large, one-toed mammalian friend is fast disappearing from city streets, even in our time.

At present, no comparable evidence of man's long-term growth is available. Our earliest ancestors could not have been very numerous and they were apparently too shrewd to become mired in Californian or Caucasian asphalt pits or equivalent preservatives. Only in a few favored caves have their remains been found, supplemented by accidental discoveries during excavations for other purposes and from exposures caused by erosion.

In America, the human frontier has been pushed back a few thousand years by the discovery of artifacts or primitive equipment of the Folsom man, whose arrowheads incorporated modern ideas of streamlining. This race was prehistoric, whether measured by the written word or by tree rings, and was doubtless beyond the reach of legend. It may seem strange at first even to consider legends in searching for the remains of our ancestors, but we need all the help we can get.

The assistance that legends are capable of giving might be illustrated by the Chinese dragons. These dragons were long thought to be the product of someone's heated or even fermented imagination. However, the discovery of the great living reptiles on the Island of Komodo in the Dutch East Indies showed that there was a physical basis for the dragon legends. Similarly, it is believed that the European legends of ogres were based upon the Neanderthal man; survivors of this race apparently were contemporaneous with our more immediate ancestors. That such a survival is possible is shown by the primitive tribes now living in Australia and elsewhere. Many specimens of the Neanderthal man have been found in Europe, from which his rather repulsive appearance has been inferred.

More ancient than the Neanderthal man is the Peking man whose remains have been found in a cave at Choukoutien in China. The relative age of these races is judged partly by the tools they made and used and by the remains of contemporary animals found nearby.

Most ancient of all apparently is the Trinil man, a few specimens of which have been found near Trinil on the Island of Java. This is not far from the home of the great dragon lizards. So low in the relative scale is the Trinil man that some doubt has been expressed as to his being really human.

A talk broadcast June 22, 1939, during the General Electric Science Forum program, from radiostation WGY, Schenectady, N. Y.

C. T. Weller is an electrical engineer in the general engineering laboratory, General Electric Company, Schenectady, N. Y.

Man's long-term growth may be summarized by stating that he has evidently lived on the present plateau for a very long time and has previously lived for much longer periods on other and definitely lower plateaus. What has made it possible for him to scale these successively higher plateaus? Apparently not any increase in physical dexterity or even the acquisition of more efficient tools, but rather the gradual development of the higher faculties of the mind.

Future Growth

What of the future? There seems to be no reason to expect that man's long-term growth will not continue and that plateaus higher than the present one will not be reached. Whether such advances will be due to further development of the mind, to a better understanding and control of the primitive subconscious, to an expansion of the senses, to a combination of these factors, or even to other factors not now suspected, cannot be forecast.

Pertinent to these prospects is a current investigation. It has been recognized for centuries that a few individuals in each generation have possessed a sort of sixth sense known as clairvoyance. The present efforts might be regarded as a quantitative analysis of clairvoyance, which is now called extrasensory perception. The results obtained show that the average score of those tested as to their ability to select or identify unseen items far exceeds the value expected from the theory of probability. The soundness of the methods used and the accuracy of the theory itself have therefore been challenged. This controversy, which is only one of many involving the various aspects of anthropology, should not be permitted to obscure the significance of the subject. If but ten per cent of the population were found to be gifted with extrasensory perception, it would be pregnant with possibilities.

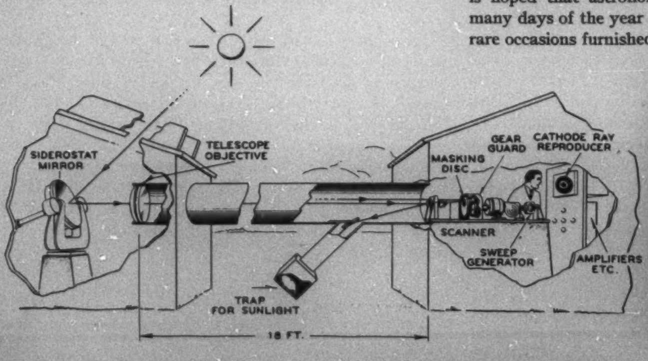
The controversies referred to raise the question as to what positions should be taken. In this respect, attitude is more important than position and I believe each of us can make a very definite contribution by endeavoring to maintain an open mind—open toward the past, open toward the present, open toward the future.

Device for Viewing the Solar Corona

ASTRONOMERS have long wished for some system that would enable them to study the solar corona—that flaming halo around the sun—by disregarding the powerful beam of the sun and the steady glare of the sky, and concentrating on the corona itself. Radio research men also have been interested, because the major disturbances of long-distance radio transmission have their origin in the sun and studies to date have indicated that a day-to-day knowledge of the activity of the corona might prove useful in predicting transmission conditions. Knowing of this need, it occurred to Doctor A. M. Skellett of Bell Telephone laboratories, New York, N. Y., that a television circuit had the necessary discrimination between steady light and variations. Apparatus embodying his idea was built in the laboratories and has been given a practical trial. A paper describing the device was presented at the recent Providence, R. I., meeting of the National Academy of Sciences.

Briefly, the apparatus (see diagram) is a television system that scans a ring around the sun. Light from the sun enters a horizontal telescope, and a sharp image of the sun is focussed on a mirror. Since this is of no use, it is reflected into a trap and dissipated. Around the image of the sun is that of the corona, and that is scanned by a combined lens and mirror. Light from this scanner is thrown into a photoelectric cell, where a direct current of varying magnitude is generated. Such a current may be considered as made up of two components: a steady current, due to light from the sky; and an alternating current due to the appearance of coronal features. In the amplifying circuits, the former is discarded and the latter is brought up to a level at which it will actuate the cathode-ray tube of a television receiver. The image may be viewed directly or recorded photographically (see illustration).

Although the development of an adequate instrument and the proving in of the method have been achieved, the real capabilities of the device will be realized only when it is used under the crystal-clear skies on a mountain top in conjunction with a telescope that, by pointing directly at the sun, will eliminate most of the glare introduced by the horizontal mounting. Under these ideal conditions it is hoped that astronomers may observe the corona on many days of the year instead of having to wait for those rare occasions furnished by solar eclipses.



Philadelphia A-C Network—Operating Results

PAUL W. CROSBY
ASSOCIATE AIEE

Twelve years' experience with the Philadelphia low-voltage a-c network, which differs materially from the more common types of networks, has proved it capable of meeting all the requirements of simplicity, reliability, and economy in the supply of high-grade electric service to the central business district of the city.

THIRTEEN years ago a paper was presented before the Philadelphia Section of the AIEE describing a low-voltage a-c distribution network for the central business district of Philadelphia. That paper described what was then a proposed system, a system that was entirely new and, in many respects, fundamentally different from the a-c network systems then being developed and placed in operation in other cities. Although thoroughly engineered and tested in the laboratory, there was no background of previous operating experience for this type of system. This network, which incorporated several novel features never before used in a distribution-system protective scheme and possessing a number of inherent advantages over other types of network systems, has long since passed the theoretical or experimental stage. It is therefore timely that the performance of the Philadelphia type of network be reviewed on the basis of operating experience since its establishment 12 years ago.

A low-voltage network may be defined as "any distribution system in which transformers at various locations have their secondary circuits tied together through the distribution mains." The transformers supplying such a network are usually fed from a number of separate primary feeders, which in turn may originate at one or more substations.

The a-c network is the modern method of electric distribution in the high-load-density areas of nearly all large cities today. Although modern, the network principle is not new, since even the early d-c distribution systems consisted of a grid of mains joined together at every street intersection. A very high degree of service reliability was obtained with the d-c network.

It was long recognized that the ideal method of a-c distribution would be a network similar to the d-c system. With such an interconnected system, all customers could be supplied from the same set of mains; advantage could be taken of diversity in the loads to install less primary-feeder and transformer capacity than would be required on a radial system, where each part of the system must be able to supply the maximum demand of its connected load; and, most important, a high degree of service continuity could be obtained. Quite some time elapsed, however, before a-c systems were developed to a point where they could compare favorably with the record of service reliability obtained with the d-c system.

A-C Network System—General

The problem with any interconnected system was that of providing means whereby faulty parts of the system could be isolated effectively and reliably without impairing service. This problem has been solved in the modern a-c network.

All secondary mains in a given area are connected together to form a solid grid of conductors. This grid is fed from a number of transformers which are supplied by a group of independent primary feeders. Protective systems have been developed whereby a failure on one feeder does not cause an interruption of service, since the load is carried on the remaining feeders. The failure of a transformer does not cause an interruption of service, since the load is carried on adjacent transformer banks. It is apparent that if a fault occurs on a primary feeder, even though the feeder breaker opens in the substation it is necessary to disconnect the feeder from the network to prevent a back-feed from the network into the fault.

The conventional type of a-c network system in operation today consists of a solid grid of secondary mains supplied from a group of *radial* primary feeders. The transformer banks are connected solidly to the primary-feeder cable and feed into the network through automatic network protectors. The automatic network protector is a low-voltage circuit breaker, automatic within itself for both tripping and reclosing under predetermined conditions by means of relays.

A fault on a radial primary feeder causes the feeder circuit breaker at the substation to open from excess current, and the automatic network protector on each transformer bank connected to the faulty feeder to open on reverse power flow from the network. The entire feeder and all of its associated transformer banks are thus removed from service, the load being carried by the remaining primary feeders and adjacent transformer banks. Similarly, when a fault in one transformer develops sufficiently, the entire primary feeder and all of its transformer banks are isolated. After repairs have been made, the feeder breaker is closed and all the associated network protectors reclose automatically, providing conditions are such that power will flow into the network and phase relations are correct. Faults on the secondary mains are depended on to burn clear as in the old d-c system.

It should be noted that in the method of radial feeder supply to a network, the entire primary feeder and all transformer banks associated with it are removed from service in event of a failure on any part of the feeder.

A local Section prize paper, presented at a meeting of the AIEE Philadelphia Section, May 8, 1939.

PAUL W. CROSBY is an electrical engineer with the Philadelphia Electric Company, Philadelphia, Pa.

The foregoing is a brief description of the a-c network system in operation in nearly all large cities today.

The Philadelphia A-C Network System

In many respects, the a-c network in Philadelphia is fundamentally different from the usual type of system found in other cities. The Philadelphia system consists of a number of interlaced *loop* primary feeders, sectionalized by means of automatic oil circuit breakers, supplying a fused secondary network as shown in figure 1. Automatic network protectors are not used. The protective scheme consists of (1) a simple balanced circulating-current pilot-wire system which trips the primary-feeder sectionalizing breakers of only the faulty loop section, and (2) copper link fuses in the secondary leads of the network transformers and in the secondary mains.

The area covered by the Philadelphia a-c network is approximately 1.4 square miles, extending from the Delaware to the Schuylkill River, Market to Pine Street, and from the Delaware River to Broad Street, Market to Vine Street. The maximum demand of the network load is about 30,000 kva, and it is supplied from 26 2,300-volt primary loop feeders. The total network area is divided into three separate and distinct networks. Each of these networks is supplied from two substations, and each such pair of substations is fed from the same generating station by 13,200-volt transmission lines. Each substation has emergency 13,200-volt tie lines to another substation supplied from a different generating station.

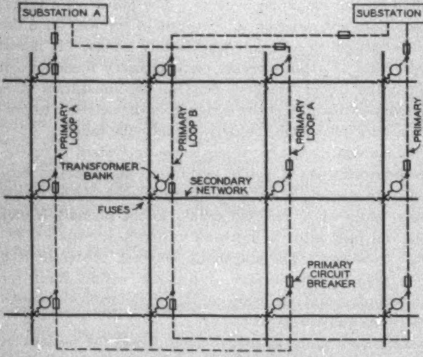


Figure 1. Secondary a-c network supplied from primary loop feeders

Both substations *A* and *B* are supplied from the same generating station, but have emergency tie lines to substations supplied from a separate generating station

The primary loop feeders supplying the network are three-wire two-phase circuits and are operated at 2,300 volts. On all but a small portion of the network, three-conductor 350,000-circular mil 13.2-kv cable has been installed to provide for possible future operation of the loop feeders at 13.2 kv. Each loop feeder extends from a substation through a number of intersections throughout the network area and returns to the same substation. Each feeder is routed through widely separated parts of the network area and interlaced with other feeders, so that so far as practicable adjacent transformer banks are supplied from separate feeders. A four-conductor cable, used for the pilot-wire protective system, parallels the primary-feeder cable.

The oil circuit breakers used for sectionalizing the primary loop feeders are of the subway type, automatic trip and manual reclosing, rated at 15,000 volts and 400 amperes, with an interrupting capacity of 100,000 kva at 15 kv. Each breaker contains six bushing type current transformers and six trip coils for the balanced pilot-wire protective system.

All of the transformers used on the network are 100 kva single-phase subway-type units. The early installations were made with standard 2,300/115–230-volt transformers with current transformers for the pilot-wire system installed in the risers of the secondary leads inside the case. All the transformers in the two Delaware network areas and about 40 per cent of the transformers in the Schuylkill network are rated at 13,800–2,300/115–230 volts. These special transformers are constructed with their high-voltage windings in six sections, connected in parallel for present operation at 2,300 volts and arranged for series connection for operation at 13,200 volts with ratio adjusters and taps for Scott connection if desired in the future.

The secondary network is a five-wire two-phase 115/230-volt system. Mains consist of three-conductor and single-conductor 350,000-circular mil 600-volt cables, generally paper-insulated and lead-covered. At the transformer intersections five-way single-polarity sectionalizing boxes are installed to junction and fuse the transformer secondary leads and street mains. Both lighting and power loads are supplied from the same set of secondary mains.

Balanced Pilot-Wire System of Protection

Each primary loop feeder is composed of a series of unit sections, each section extending between sectionalizing oil circuit breakers. The network transformer bank and sectionalizing breakers are included in the unit section. Figure 2 is a schematic diagram showing the protective system of a complete primary loop feeder. Each unit section, shown in detail in figure 3, consists of three branches around the point where the primary winding of the network transformer is connected to the feeder. Current transformers in each of the three branches of the unit section are interconnected to form the balanced circulating-current pilot-wire circuit. Trip coils in the oil circuit breakers are connected across the pilot-wire circuit at each end of the unit section.

Under normal operating conditions, the relative polarity of the current transformers is always such that circulating current flows in the pilot-wire circuits, with zero or negligible current in the trip coils. In the event of a fault anywhere in a unit section, primary cable, or transformer, there is a change from the normal relative polarity of the associated current transformers; the normal pilot-wire balance is disturbed, so that current flows through the trip coils, tripping the oil circuit breakers at each end of the faulty unit section. The back-feed from the low-voltage network blows the fuses in the transformer secondary leads and that one unit section is completely isolated. Back-up protection, or a second line of defense in the event of failure of a sectionalizing breaker to operate, is provided by means of overload relays in the substation and the fuses in the network-transformer secondary leads.

The protective system for each unit section of feeder is responsive only to fault conditions within the section. Only one transformer bank and its associated section of primary cable are isolated in case of a primary-cable or transformer fault. All the other transformer banks remain in service, being supplied from the two parts of the loop feeder that have been separated by isolation of the faulty unit section. The occurrence of a fault thus causes a minimum of disturbance to the remainder of the system and permits the installation of a reduced amount of reserve transformer capacity, irrespective of the number of primary feeders.

One of the outstanding features of the sectionalized-loop-feeder system with pilot-wire protection on the individual unit sections is the protection provided for faults in network transformers. The absence of such protection is a recognized problem in the conventional automatic protector system, in which the overcurrent relays at the substation cannot be set to respond to certain types of transformer faults until the faults have progressed to an undesirable degree. Notwithstanding this added feature, the sectionalized-loop-feeder protective system is extremely simple, an important factor in distribution-system equipment that must be installed at widely scattered locations in a distribution area under adverse conditions frequently encountered in underground vaults.

Operating Results

The operating record of the Philadelphia network system is one of highly satisfactory performance. During the 12-year period of network operation, there have been 70 primary-cable and 14 transformer failures. In every one of these failures the faulty equipment was isolated successfully, without any evidence of unsatisfactory breaker performance, and, with one exception, without interruption to any network customer.

In one of the 70 primary-cable failures an open trip-coil circuit on the sectionalizing breaker adjacent to the fault prevented operation of the breaker. In this case three sets of transformer secondary fuses were blown and the station breaker opened on one end of the loop feeder. Here the inherent self-protecting characteristic of the system is apparent. A cable failure was followed by the non-operation of the protective device, and, in spite of this coincidence, no load was lost and no thermal failure of cable or transformers resulted—a test of the adequacy of the back-up protection.

Three of the 14 transformer failures were associated with primary-cable failures. The primary sectionalizing breakers operated, but the transformer secondary fuses either failed to blow or did not blow soon enough to prevent damage to the network transformer. These transformers were each located at network intersections where, because of the relatively high impedance to adjacent transformer banks or a limited number of adjacent banks, the fault current was not sufficient to assure prompt operation of the fuses. No network customers were interrupted on these transformer failures.

In another case of delayed and incomplete fuse blowing on a primary-cable fault, an undersized transformer neutral lead became overheated and caused a fire in a manhole at a street intersection. It was necessary temporarily to interrupt the mains for a block in each direction from that intersection so that a man could go into the manhole and cut free the faulted cable. This temporary interruption was the only case of network customers being isolated on a primary-cable fault. Smaller fuses are now being used in locations where the back-feed is limited, and prompt fuse blowing is now assured on primary-cable faults.

There have been a few cases of sectionalizing breakers opening and isolating unit sections for causes at the time unknown. In some of these cases, the same section tripped two or three weeks later and a cable fault was

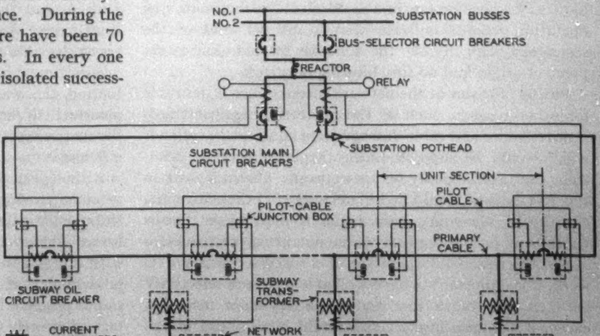


Figure 2. Single-line diagram of sectionalized loop primary feeder supplying fused secondary network, showing protective system

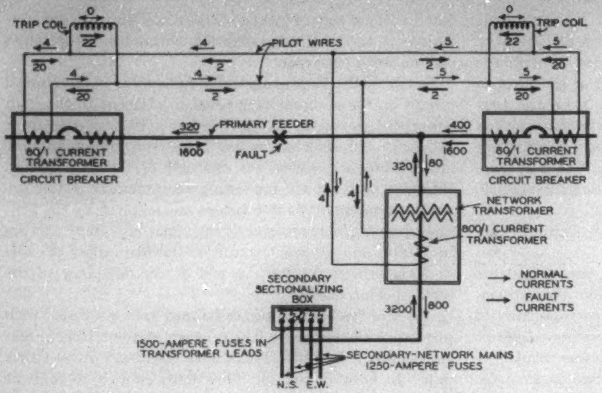


Figure 3. Schematic diagram of unit section of primary loop feeder, showing operation of protective system

Current values shown are assumed for purpose of illustration only

located on this subsequent tripping. There have been two operating errors, one of which caused an entire loop feeder to trip out, and the other caused a unit section to trip. No customer interruptions resulted from these operations.

The use of fuses in the secondary mains of the Philadelphia network is another fundamental difference from the usual type of network system, although in recent years fuses have been installed in several networks in other cities. One of the basic principles in the original design was to provide a means for isolating faulty equipment from the system just as quickly as possible, with a minimum of disturbance to the remainder of the system and a minimum of damage to the equipment at fault. The operation of secondary fuses has demonstrated that faults on secondary mains are quickly and selectively isolated, consequently with minimum damage to cables and minimum disturbance to customers on other mains.

Fuses in the secondary mains have not resulted in entire block outages at times of cable-main faults, as might be expected. Experiences to date have been that fuse blowing occurred at only one end of the main, the fault being finally cleared by burning open, with interruption of service to only a few customers in the block. Furthermore, the operating records indicate that in 84 per cent of the secondary main trouble, the fault has burned clear at the point of origin and no fuse blowing occurred.

Fusing of mains at the network intersections is desirable for other reasons, such as the protection against transformer failure and cable damage from continued overloads which would be imposed during the burning-off of tenacious faults on a solidly tied-in network. From reports on the operation of solidly tied-in networks in other cities, the clearing of secondary-main faults is a problem that is warranting serious study by some operating companies.

For the successful operation of a fused-secondary network, it is important to have a reliable degree of selectivity between the transformer and secondary-main fuses because, if the transformer fuse should blow ahead of the fuse in the main, in the event of a main fault, it would reduce the total fault current and reduce the certainty of the fuse blowing in the main. The result would probably be a sustained overload on adjacent network transformers and cable mains with possible thermal failure of transformers and other mains. Operating experience has conclusively demonstrated that the selected sizes of transformer and main fuses give the necessary degree of selectivity. During the 12 years' operating experience, no transformer fuse has ever blown on a main fault, nor has a main fuse ever blown on a primary-cable or transformer failure. The fuse sizes are selected to be responsive only to currents of fault magnitude, 1,500- and 1,250-ampere fuses being used in the transformer leads, and 1,250- and 1,000-ampere fuses in the secondary mains. The fuses are of the simple copper link type with ratings based upon full load.

In the early development of the original system design, particular attention was paid to the ratio of current transformers, the size of pilot wire, and the volt-ampere characteristics of the a-c trip coils of the sectionalizing circuit breakers. It is important that the current transformers have similar characteristics throughout their operating range and that the voltage drop across the pilot-wire circuit be limited to a value that will avoid faulty operation of sectionalizing circuit breakers on a through fault, that is, a fault in another section of the loop feeder, or on the network. The factor of safety against such faulty operation on through faults is dependent, among other things, on the length of section between sectionalizing breakers and on the magnitude of the current through the section.

There have been instances of faults involving the flow of fault current through sections from 3,000 to 5,000 feet in length, none of which resulted in faulty operation of breakers at the ends of the long sections. Though the fault impedance may have been such that the fault current was limited, this was evidently not the only factor preventing incorrect tripping, since one fault was a solid three-conductor short-circuit to ground and involved a section 3,500 feet in length.

Although designed initially for the supply of service at secondary voltage, it has been found that the sectionalized loop feeder system lends itself readily to the supply of service at primary voltage. This has been done flexibly, and with a high assurance of continuity of service, closely approaching that afforded by two services from separate radial primary feeders. The primary services have been tapped directly to the loop sections without any additional sectionalizing facilities. The high degree of assurance of service continuity arises out of the fact that, based upon operating experience during the past several years, the probable frequency of faults on a particular loop section is about once every 25 years.

Major System Disturbances

The individual network areas have successfully coped with several interruptions of supply to one or both of the substations supplying them. With the loss of supply to one of the two substations feeding a network area, the other station continued to carry not only the network load but also, by back-feed through the network and loop feeders, a number of radial feeders from the substation in trouble. The maintaining of service by back-feed from the network, at such times, is in marked contrast to the operation of the usual type of a-c network system, in which all transformers of the interrupted substation would be disconnected from the network on reverse power flow through the network protectors.

In the cases of simultaneous loss of supply to both substations feeding a network area, service was readily restored without operations of loop primary sectionalizing circuit breakers or blowing of secondary fuses. With such disturbances, the resumption of normal supply conditions has been found to be an absolutely clean-cut and quick procedure.

In major disturbances, the network load and the radial load from network substations have been carried with either no interruption or (in the event of loss of supply to both substations) with only a short interruption because:

1. Supply from another generating station is immediately available to each network substation via tie lines.
2. All network feeders and transformers remain connected because the protective system is unaffected by direction of power flow at any single point.
3. Reserve capacity is inherent in the primary loop feeders.
4. Secondary main and transformer currents do not blow fuses.

Inspection of Network Equipment

The simplicity and ruggedness of the loop oil circuit breakers and fused sectionalizing boxes has resulted in low operating and maintenance costs. The protective equipment is called upon to function only under fault conditions in a single unit section and this is undoubtedly an important factor in reducing the operating and maintenance costs on the protective equipment.

An inspection is made every 6 to 12 months to determine the condition of transformers, oil circuit breakers, secondary sectionalizing boxes, and pilot-wire control system. Because of the simplicity of the network equipment, the tests and inspections are relatively simple and easily made. There are no relays or moving contacts in the control circuit, nor any equipment requiring highly sensitive and "hair trigger" adjustments for satisfactory operation.

Routine inspections include the checking of trip-coil adjustments, operating mechanisms of the oil circuit breakers, air tests on transformer and circuit-breaker tanks, continuity of pilot-wire conductors and secondary mains, and observation of the general condition of the equipment. The pilot cables and leads from current transformers and trip coils are terminated in junction boxes provided with test clips to facilitate testing. The first complete inspection of the oil circuit breakers was made in 1935, and no conditions of distress were found to exist after their several years in service. Continuity of the loop feeders is checked twice weekly by the substation operator opening the breaker on one end of each feeder and noting the change in the ammeter reading on the other end. It was only by this method that many of the primary faults near the midpoint of a loop feeder were indicated, so slight was the disturbance caused by losing only one section of feeder and its associated transformer bank.

Investment and Operating Costs

There are certain inherent economic advantages in the sectionalized loop-feeder system over the conventional radial-feeder system. Since only one unit section with its one associated transformer bank is isolated by a primary-cable or transformer failure, a minimum of additional load is thrown on adjacent transformer banks. This feature, in addition to requiring a minimum of reserve transformer capacity, permits a simplified routing of primary feeders with a consequent saving in the length of primary cable required.

In any final choice between alternative systems, a comparison almost never can be made on the basis of the technical aspects alone; a comparison of the costs must also be given due consideration. Owing to the diversity of conditions met in various localities, it is obviously impossible to make definite statements as to the relative costs of different types of a-c secondary network systems.

From a study of published data on other network systems, however, it is evident that the advantages of the Philadelphia type of network can be obtained with a capital investment no greater than that required for the conventional type of system, and, because of the extreme simplicity of its protective scheme, the operating and maintenance costs are considerably lower. The cost of additional equipment such as pilot cable and primary sectionalizing circuit breakers is amply balanced by savings in other directions, such as the avoidance of the use of expensive and highly sensitive relays and network protectors, and the need for a minimum of spare transformer capacity.

Conclusions

The original design of the Philadelphia a-c network system has long since passed the theoretical or experimental stage. The 12 years' experience in practical application has proved it capable of meeting all the requirements of simplicity, reliability, and economy in the supply of high-grade service to the Philadelphia central district. This commendable record has been obtained from a wide range of operating experiences which have thoroughly tested the system in practice, and conclusively demonstrated the advantages of sectionalized primary loop feeders and a fused secondary network.

News
Of Institute and Related Activities

Winter Convention to Feature Lecture on Atomic Disintegration

A POPULAR lecture on "Atomic Disintegration" by Doctor Enrico Fermi, distinguished physicist and winner of the 1938 Nobel Prize in physics, will be one of the high lights of the Institute's forthcoming winter convention, to be held in New York, N. Y., January 22–26, 1940, with headquarters at the Engineering Societies building. Doctor Fermi's lecture will be delivered on Wednesday evening, January 24, in connection with the presentation of the Edison and Hoover Medals, and will be followed by demonstrations of atomic disintegration by Doctor John R. Dunning, professor of physics, Columbia University.

Atomic disintegration or "fission" by neutron capture is a newly discovered physical phenomenon which may some day be of great significance to engineers on account of the relatively enormous amount of energy liberated in such atomic explosions. These recent experiments mark a long step forward toward the possible utilization on the earth of some of the vast stores of atomic energy now known to furnish the energy of the sun and stars.

Doctor Fermi by his work on the transmutation of atomic nuclei blazed a trail of his own, which led to winning the Nobel Prize. He has been working with Doctor Dunning and the research group in physics at Columbia University using the cyclotron in experiments on the physics of atomic nuclei. Doctor Dunning is a versatile and resourceful demonstrator, who will illustrate by experiments some of the phenomena of which Professor Fermi will speak. The lecture and demonstration will afford an exceptional opportunity for our members to keep abreast of the very latest physical experimentation.

Technical Sessions and Conferences

Nineteen technical sessions have been proposed in 12 different fields of technical-committee activity. These sessions embrace many papers that will present new treatments of existing theories, new designs of electrical apparatus, and the latest in operating practice. The sessions which have been proposed are as follows: transportation (2), industrial power applications (1), electrical machinery (2), production and application of light (1), power generation (1), protective devices (3), power transmission and distribution (2), communication (3), automatic stations and basic sciences (1), electronics (1), instruments and measurements (1), and electric welding (1).

In addition to the 19 technical sessions 5 technical conferences have been proposed as follows: test code for synchronous machines, sound, feedback amplifiers, networks, and increasing the use of electronic devices. These conferences will be informal, some of them conducted as round-table discussions.

Further details of the program will be announced in the January 1940 issue.

Test Code for Synchronous Machines

Doctor Enrico Fermi, Nobel Prize winner who will speak at the coming AIEE winter convention

The technical conference planned on the test code for synchronous machines will take the form of an open meeting of the Institute's subcommittee which has had this code under preparation for some years. Suggestions and comments are cordially invited. It is requested that they be submitted in writing, so far as possible, but opportunity for open discussion will be given, especially on important or controversial points.

The latest edition of the proposed test code was printed in January 1937. Copies may be had upon request to H. E. Farrer at Institute headquarters. Some changes have since been adopted, particularly in the section on synchronous machine quantities (reactances and time constants), to the effect that reactance values determined from three-phase short-circuit tests shall be based upon the a-c components of all three current waves, instead of one symmetrical wave; also, saturation is taken into account by the introduction of "rated current" and "rated voltage" values. A new section on the determination of the synchronizing power constant, *Pr*, is being prepared.

Many other changes have been suggested, not only as to content and language, but as to arrangement, symbols, illustrations, etc. All types of suggestions will be welcomed at the conference, and given consideration if presented in writing. The discussion will be concerned primarily with matters of content and language. Other matters will be heard, so far as time permits. Definite text changes can probably not be adopted at the conference, but will have to be worked out later by the subcommittee, along with editorial details. It is hoped that this can be done in a few months' time, and that the test code can be reported as complete for issue sometime in 1940. All those interested are therefore urged to review the code and take advantage of this opportunity to present their suggestions.

Entertainment

Plans for social events at present include a smoker to be held on Tuesday evening, January 23, and a dinner-dance on Thursday evening, January 25. Special entertainment for women guests will be arranged by the women's entertainment committee, of which Mrs. G. S. Rose is chairman. Inspection trips to places of interest in and about the city will be arranged during the week and on Friday.

Winter Convention Committee

The personnel of the 1940 winter convention committee is as follows: A. F. Dixon, *chairman;* J. W. Barker, T. F. Barton, G. E. Dean, E. E. Dorting, L. C. Miller, A. G. Oehler, J. H. Pilkington, C. S. Purnell, George Sutherland, and W. W. Truran.

Picou Receives Mascart Medal. The Mascart Medal of the Société Française des Électriciens, awarded every three years, has been given in 1939 to R. V. Picou, founder member and honorary president of the society, who is known particularly for his work on magnetism and supplementary poles in machines. The medal, which was established in 1923 in honor of the founder of the society, was last awarded (1936) to the late A. E. Kennelly, honorary member and past president of the AIEE.

CIGRÉ Proceedings. Complete proceedings of the tenth session of the International Conference on High-Voltage Systems (CIGRÉ), held in Paris, France, June 26 to July 9, 1939, will be published in book form early in 1940. They will be issued in French, and, if sufficient advance demand is expressed, in English as well. Copies may be subscribed for in advance by writing Tribot Laspiere, general secretary, CIGRÉ, 54, Avenue Marceau, Paris, France.

AIEE Board of Directors Meets at Institute Headquarters

THE regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on October 27, 1939.

There were present: *President*—F. Malcolm Farmer, New York, N.Y. *Past Presidents*—John C. Parker and W. H. Harrison, New York, N.Y. *Vice-Presidents*—T. F. Barton, New York, N.Y.; F. C. Bolton, College Station, Tex.; Chester L. Dawes, Cambridge, Mass.; H. W. Hitchcock, Los Angeles, Calif.; A. H. Lovell, Ann Arbor, Mich.; C. T. Sinclair, Pittsburgh, Pa.; J. M. Thomson, Toronto, Ont.; and Albert L. Turner, Omaha, Nebr. *Directors*—C. R. Beardsley and H. S. Osborne, New York, N.Y.; V. Bush, Washington, D.C.; Mark Eldredge, Memphis, Tenn.; R. E. Hellmund and C. A. Powel, East Pittsburgh, Pa.; F. H. Lane and L. R. Mapes, Chicago, Ill.; K. B. McEachron, Pittsfield, Mass.; F. J. Meyer, Oklahoma City, Okla.; D. C. Prince, Philadelphia, Pa.; and R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N.Y. *National Secretary*—H. H. Henline, New York, N.Y.

Minutes of the meeting of the board of directors held August 4, 1939, and of a special meeting of the executive committee held October 20, 1939, were approved.

Report was made and approved of actions of the executive committee as of September 21, 1939, on applications, as follows: 18 applicants transferred to the grade of Fellow; 23 applicants transferred and 7 elected to the grade of Member; 37 applicants elected to the grade of Associate; 12 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held September 14 and October 19, 1939. Upon recommendation of the board of examiners, the following actions were taken: 1 applicant was reinstated to the grade of Fellow; 9 applicants were elected to the grade of Member; 42 applicants were elected to the grade of Associate; 763 Students were enrolled.

Monthly disbursements were reported by the finance committee, and approved by the board, as follows: $14,917.03 in August, $16,966.69 in September, and $27,644.55 in October.

Upon recommendation of the finance and Section committees, the following resolution was adopted:

WHEREAS the Board of Directors, on August 8, 1922, authorized Sections' discretion in the expenditure of the Sections' meeting appropriations to cover social activities, and

WHEREAS some Sections have assumed this latitude to cover the payment of additional traveling expenses of delegates to national and District meetings above the amounts provided in the budget, be it

RESOLVED: That the Sections be advised that this practice does not come within the latitude extended the Sections.

A budget for the appropriation year beginning October 1, 1939, was adopted as submitted by the finance committee and revised by the board. (Information about the budget appears elsewhere in this issue.)

The board voted, with regret, to release the Vancouver Section from the responsibility of acting as host for the 1940 Pacific Coast convention, because of the war situation, and accepted the invitation of the Los Angeles Section to hold the convention in Los Angeles or vicinity.

Authorization was given to the Dallas Section for a change in name to "North Texas Section" and an extension of territory.

Upon recommendation of the standards committee, the board approved the appointment of Institute representatives as follows:

R. T. Henry, Stanley Stokes, D. M. Jones, and A. C. Monteith, on the NEMA-EEI-AIEE Joint Committee on Insulation

I. A. Yost on the Sectional Committee on Industrial Lighting, A11, to succeed C. H. More, resigned

C. L. Dawes and W. N. Zippler on the Sectional Committee on Insulated Wires and Cables, C8, to succeed E. B. Meyer, deceased, and Doctor J. B. Whitehead, resigned

Doctor Reinhold Rudenberg on the Sectional Committee on Rotating Electrical Machinery, C50, to succeed Doctor A. E. Kennelly, deceased

D. F. Miner, representative, and A. M. deBellis and A. H. Schirmer, alternates, on the Sectional Committee on Preferred Voltages—100 Volts and Under.

As recommended by the standards committee, the board authorized withdrawal by the AIEE from joint sponsorship with the National Electrical Manufacturers' Association of the Sectional Committee on Electric Welding Apparatus, C52, in favor of sole sponsorship by the American Welding Society.

The resignation of E. E. George as vice-president of the Institute representing the Southern District (4), on account of removal from the District, was accepted with regret, and Professor Fred R. Maxwell, Jr., University of Alabama, Tuscaloosa, Ala., was elected vice-president in his place.

A. H. Kehoe was appointed a representative of the Institute on the standards council of the American Standards Association for the three-year term beginning January 1, 1940, to succeed V. M. Montsinger, whose term will expire at the end of the present calendar year. H. E. Farrer, H. H. Henline, and E. B. Paxton were reappointed alternates for the year 1940.

C. R. Beardsley, C. L. Dawes, Mark Eldredge, A. H. Lovell, and C. A. Powel were elected as the board members to serve on the national nominating committee for the year 1939–40, and T. F. Barton and H. S. Osborne were designated as alternates.

Report was made of notification from The Engineering Foundation of appropriations by Foundation, for the fiscal year 1939–1940, for three research projects sponsored by the AIEE, viz: Stability of Impregnated Paper Insulation, Insulating Oils and Cable Saturants, and work of the Welding Research Committee.

The board accepted an invitation for the AIEE to be represented on the American Research Committee on Grounding, and appointed C. T. Sinclair as the Institute's representative.

At the meeting of the board of directors on May 26, 1939, there was submitted a proposal of the Westinghouse Electric and Manufacturing Company for the establishment, with the income from funds to be donated by the company, of a graduate scholarship to be administered by the AIEE, and to be known as the Charles Le Geyt Fortescue scholarship, as a perpetual memorial to the late Charles Le Geyt Fortescue. The board accepted the proposal and authorized the president to appoint a committee to collaborate with the Westinghouse company in working out the details. The president subsequently appointed a committee, consisting of C. A. Powel (chairman), R. E. Doherty, D. C. Prince, E. B. Roberts, and W. I. Slichter. The committee submitted, at this meeting of the board, a proposed trust agreement and proposed bylaws for the Charles Le Geyt Fortescue scholarship committee, which will make the awards. The board authorized the president and the national secretary to sign the trust agreement, approved the bylaws, and authorized the president to appoint the first committee.

The board authorized an "Address of Greeting" from the Institute to the School of Engineering of Columbia University on the occasion of the 75th anniversary of the School of Engineering.

Report was made of a testimonial to Past-President Charles F. Scott, signed individually by the members of the executive committee of the Institute and included in a bound volume of testimonials, which was presented to Doctor Scott at a dinner given by the Connecticut Section in his honor, on the occasion of his 75th birthday.

It was reported that a scroll of honor, signed by the presidents of several organizations, including the AIEE, was awarded to Dr. Lee de Forest on September 22 at the celebration of de Forest Day at the New York World's Fair.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Graduate Program at Carnegie Tech. Establishment of a graduate program in electrical engineering at Carnegie Institute of Technology, Pittsburgh, Pa., has been made possible by a grant of $50,000 from the Buhl Foundation, according to recent announcement. Planned to enable trained engineers to engage in industrially useful study and research, the program will be directed by Doctor B. R. Teare, Jr. (A'29, M'36) whose biography appeared in the November issue, page 490. Beginning with the current academic year, the grant will support the graduate courses in electrical engineering for five years.

Future AIEE Meetings

Winter Convention
New York, N.Y., January 22–26, 1940

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Place and date to be announced

The Institute Budget for the Year 1939–40

AN INCREASE in the number of pages of technical papers and discussions in the monthly journal, ELECTRICAL ENGINEERING, and in the 1939 annual bound volume of TRANSACTIONS—an increase in the rate of traveling expenses for delegates to Institute meetings and to the District conferences for which such allowances are granted (from $7^{1}/_{2}$¢ to $8^{1}/_{2}$¢ per mile one way) effective January 1, 1940—the addition of one person to headquarters' staff to assist in the work of the standards and technical program committees—an initial payment of $5,000 to a pension fund reserve—are provided for in the budget of income and expenditures for the appropriation year beginning October 1, 1939, which the board of directors adopted at its meeting on October 27, 1939.

In making its budget recommendations to the board the finance committee endeavored, with respect to the estimate of income, to allow for a probable loss of dues revenue which will result from the conditions existing in those countries involved in the present war. The expenditure budget was also presented after careful study of the financial requirements for the year as estimated by the standing committees. As a result of modifications made at the meeting of the board of directors, for the time being the budget is slightly out of balance in that the budgeted expenditures exceed the anticipated income for the year by about $2,000. The finance committee, however, will be prepared at the January meeting of the board of directors to recommend adjustments of the budget to bring it in balance.

A detailed tabulation of the budget appears herewith. From this it will be seen that practically all activities are being afforded at least as much financial support as last year; in some cases an increased appropriation is being granted to cover an enlarged program of activities.

The July issue of ELECTRICAL ENGINEERING carried in the news section (pages 305–317) the complete report of the Institute board of directors for the fiscal year ending on April 30, together with financial statements for the corresponding period. In this report will be found an extensive statement covering such activities as national and District meetings of the Institute, Section and Branch activities, etc., making it unnecessary to repeat at this time the details underlying the appropriations for the principal activities. Should further information be desired, this can be obtained upon correspondence with Institute headquarters.

Each year the board of directors endeavors to make sure that the budget adopted will make possible a proper relative emphasis on the different phases of Institute activities and will limit the annual expenditures to the amount of anticipated income. Membership dues, of course, comprise the principal source of Institute revenue, so that the success of all work planned for in the budget depends largely upon the prompt collection of dues.

Institute Income and Expenses for Year Ending September 30, 1939, and Budget for Year Ending September 30, 1940

	Actual Income and Expenses, Year Ending 9-30-39	Budget for Year Ending 9-30-40
Income		
Dues	$198,745.84	$201,000.00
Students' fees	12,677.50	13,000.00
Entrance fees	6,411.49	6,800.00
Transfer fees	950.00	1,000.00
Advertising	28,641.02	30,000.00
ELEC. ENGG.—non-mem. subscriptions	15,295.51	14,000.00
TRANS. subscriptions	7,442.71	7,300.00
Miscellaneous sales	12,790.99	10,300.00
Badge sales	1,768.00	1,800.00
Interest on securities	7,755.49	6,800.00
Total	$292,478.55	$292,000.00
Expenses		
Publications:		
Text matter (ELEC. ENGG. & TRANS.)	†$66,121.24	*$75,170.00
TRANS. SUPPLEMENT	195.41	350.00
Preprints	8,940.00	8,800.00
Advertising section	14,304.62	15,600.00
Year Book	6,482.67	6,750.00
Miscellaneous expense	1,310.93	1,900.00
Institute meetings	13,726.16	14,750.00
Institute Sections:		
Appropriations	23,376.17	24,300.00
Other expenses	5,783.03	5,950.00
Institute Branches:		
Meetings expenses	1,058.06	1,100.00
Other expenses	2,077.16	2,500.00
Committees:		
Code of prin. prof. conduct		50.00
Edison Medal	146.61	150.00
Finance	1,600.00	800.00
Headquarters	202.10	300.00
Lamme Medal	30.57	160.00
Legislation		50.00
Membership	7,770.94	8,350.00
Model registration Law	187.53	
Standards	6,542.60	8,300.00
Technical	271.79	300.00
Traveling Expenses:		
Geo. Dist. exec. committees	3,229.29	3,000.00
Section delegates to summer conv.	11,769.93	6,500.00
Counselor delegates to summer conv.	1,393.89	1,250.00
Dist. secys. to summer conv.	1,021.65	1,150.00
District Student conferences	6,066.85	6,500.00
President's appropriation		$ 1,500.00
Vice-presidents	435.37	570.00
Board of directors	5,861.47	5,900.00
National nominating committee	1,020.79	1,200.00
AIEE representatives		100.00
Administration:		
Headquarters' salaries	35,311.50	36,700.00
Postage	3,887.47	4,000.00
Stationery & printing	3,372.82	3,700.00
Office equipment	342.71	400.00
Trav. expense, insurance, misc. supplies & services	3,096.72	3,275.00
Paper prizes	366.80	515.00
Joint activities:		
American Engineering Council	9,000.00	6,000.00
American Standards Assn	1,500.00	1,500.00
Engrs. Council Prof. Dev	850.00	850.00
Engg. Foundation research proj.:		
Impregnated paper insulation	250.00	250.00
Insulating oils & cable saturants		250.00
Welding	250.00	250.00
Engg. Soc. Employment Service	1,762.92	1,108.00
Engg. Soc. Library	9,689.30	9,900.00
Hoover Medal		150.00
John Fritz Medal	251.92	
United Engg. Trustees building assessment	10,984.80	10,985.00
U. S. Natl. Com. I. C. I	300.00	300.00
Miscellaneous printing, etc		3,400.00
Authors' reprints	2,231.67	
Reprints of standards	758.28	
TRANSACTIONS Index	3,855.10	
Miscellaneous	80.09	
Other expenses		
Membership badges	1,244.04	1,750.00
Text paper & env. in storage	844.39	
Pension Fund Reserve		5,000.00
Miscellaneous	708.28	310.00
Total	$281,865.64	$293,893.00

† Actual expense $68,626.90, including paper costs paid for previously.

* Actual budget of $75,870.00 reduced by text paper inventory of $700.00

Executive Committee of AIEE District 1 Meets

The executive committee of the AIEE North Eastern District met October 13, 1939, at Schenectady, N. Y. Those present were:

C. L. Dawes, vice-president, North Eastern District
R. G. Lorraine, secretary, North Eastern District
B. M. Strong, chairman, District committee on Student Branches
G. W. Dunlap, representing District membership committee
A. C. Stevens, past vice-president, North Eastern District
C. W. LaPierre, chairman, Schenectady Section
B. M. Hunter, vice-chairman, Schenectady Section
C. W. Henderson, chairman, Syracuse Section
True McLean, chairman, Ithaca Section
J. P. Wood, secretary-treasurer, Ithaca Section
C. F. Savage, chairman, Lynn Section
R. G. Porter, representing executive committee of Boston Section
M. E. Scoville, secretary-treasurer, Pittsfield Section
J. H. Milbyer, secretary-treasurer, Niagara Frontier Section
V. Siegfried, representing chairman of Worcester Section
R. S. Judd, chairman, Connecticut Section
A. G. Conrad, secretary-treasurer, Connecticut Section
W. B. Hall, chairman, Providence Section
W. F. Cotter, vice-chairman and secretary, Rochester Section
H. D. Griffith, secretary, Springfield Section
K. B. McEachron, AIEE Director
H. H. Race, chairman, AIEE Sections committee

Vice-President Dawes presided. On behalf of the general convention committee for the 1940 summer convention, two meetings were reported, and the formation of working subcommittees on entertainment and banquets, trips, hotels and registration, transportation, sports, student activities, publicity, women's entertainment, finance, general arrangements and co-ordination.

All these committees have reported preliminary plans and budgets.

The invitation of the Rochester Section for a District meeting to be held in Rochester in 1941 was accepted by the committee. Plans for having President Farmer visit the various Sections of the District were discussed and joint meetings considered.

The committee nominated E. S. Lee (A'20, F'30) Schenectady, N. Y., for AIEE vice-president, District 1, for 1940–41. W. B. Hall was elected District representative on the national nominating committee. Suggestions for Institute president or director are to be sent by the District executive committee to the District vice-president and District secretary.

The following were appointed to the District co-ordinating committee, in addition to the vice-president, secretary, and chairman of the committee on Student Branches:

R. H. Bryant
C. F. Savage
J. C. Balsbaugh

The following were appointed judges for the District prize awards for papers presented during 1938–39:

C. W. LaPierre
J. G. Patterson
H. M. Turner

Chairman Race of the AIEE Sections committee, emphasizing the importance of Section activities in the progress of the Institute, suggested in addition to the activities already carried on by most Sections (see report, *EE, Oct. '39, pp. 436–7*) the following:

1. Appointment of a committee on legislation, either alone or in co-operation with other local engineering organizations.
2. Appointment of a committee on economic and social affairs, alone or co-operatively, to stimulate and organize group interest in such considerations.
3. Appointment of a committee on vocational guidance to provide speakers and distribute material on the engineering profession.
4. Stimulation of active participation by younger members, through follow-up of student members moving into Section territory, and by giving young men in the Section opportunities for active Section work.

Doctor Race announced two booklets to be available from Institute headquarters soon: one on "Section Activities," and one, called "The Electrical Engineer," which will provide preparatory school students and vocational counselors with information about the profession. This booklet and the ECPD publication, "Engineering—a Career, a Culture," were suggested for the use of Section vocational guidance committees.

Membership activities, District financial matters, and other topics were also discussed at the meeting.

Doctor Bláthy Dies. Doctor Otto Titus Bláthy, Hungarian inventor and electrical engineer, died at Budapest, Hungary, September 26, 1939. Born in 1860, he had been employed since 1883 by the electrotechnical factory of Ganz and Company, Budapest. He made a number of contributions to electrical development during the early history of the art, and continued to perform valuable work until the time of his death. He had received various honors, both in his own and other countries.

AIEE Minnesota Branch Given "Best Society" Award

The AIEE Student Branch at the University of Minnesota, Minneapolis, received the Best Society Award presented by the "Tech Commission" to the most outstanding student organization in the Institute of Technology during the school year 1938–39. The award is made on the basis of a point system: The percentage of eligible students who are members of the society, minus a "handicap" calculated on the basis of past membership records, determines membership points; activity points ranging in number from 2 to 20 are given for such activities as open house, electrical-engineering show, banquets, field trips, meetings, floats, field-day participation, cup, social gatherings, and others. Membership points multiplied by 0.4, plus activity points multiplied by 0.6, give the organization's final score, which for the AIEE Branch was 93.2. Current officers of the Branch shown here with the Best Society plaque are, left to right, Robert Lyons, vice-chairman; Professor J. H. Kuhlmann, counselor; Robert MacDonald, chairman (holding plaque); Elmer Brickman, secretary-treasurer.

Dallas Section Becomes North Texas Section

By action of the AIEE board of directors on October 27, 1939, the name of the Dallas Section has been changed to North Texas Section. The Section's territory has been extended to include the area west and northwest of the present Section territory, comprising 133 counties in all.

The Dallas Section was organized May 18, 1928. Its officers for 1939–40 are C. W. Mier (A'25, M'31) engineer, Southwestern Bell Telephone Company, Dallas, *chairman;* H. R. Pearson (A'36) engineer, Dallas Power and Light Company, Dallas, *secretary.*

AIEE National and District Prizes for Papers

Provision in the Institute's 1939–40 budget has been made for cash awards to accompany the national and District prizes for initial and Branch papers to be awarded during the current year, as indicated below.

All technical papers presented before the Institute during the year are eligible under the AIEE paper prize regulations for competitive consideration for one or more of the established prizes, regardless of whether presented before a Branch meeting, a Section meeting, a District meeting, or a national convention, the several classes providing for equitable competition. With the exception of the prizes for Branch papers, both District and national prizes are awarded each spring for papers presented during the preceding calendar year. For Branch papers, both national and District prizes are awarded on the basis of the academic year, July 1 to June 30, inclusive.

National prizes that may be awarded annually, and those to be accompanied by cash awards during the current year, are as follows:

1. Best paper prizes (certificates):
   - *Engineering practice*
   - *Theory and research*
   - *Public relations and education*
2. Prize for initial paper ($100 and certificate)
3. Prize for Branch paper ($100 and certificate)

District prizes that may be awarded annually, together with the cash awards provided for the current year, are:

1. Prize for best paper (certificate)
2. Prize for initial paper ($25 and certificate)
3. Prize for Branch paper ($25 and certificate)
4. Prize for graduate student paper (certificate)

Although all papers presented are *eligible,* there is no provision for automatic consideration of papers, except that those approved by the technical program committee and presented at national conventions or District meetings will be considered by the national prize committee for the national "best paper" and the "initial paper" prizes without being offered formally for competition. All other papers for which prize consideration is desired must be *submitted* specifically for that purpose, through the District secretary for District prizes, or through the national secretary's office for the national prizes.

Deadline Dates

Papers to be considered for 1939 national prizes must be submitted not later than February 15, 1940. Papers to be considered for the District "best" and "initial" paper prizes must be submitted on or before February 15, 1940; for the District, Branch, and graduate student paper prizes, before July 15, 1940 (for papers presented during the academic year ending June 30, 1940). Those wishing further information may obtain a booklet entitled "National and District Prizes" from AIEE Headquarters, 33 West 39th Street, New York, N. Y.

John Fritz Medal Awarded to Late C. F. Hirshfeld

The John Fritz Gold Medal for 1940 has been awarded posthumously to Doctor C. F. Hirshfeld (A'05, F'36), by unanimous vote of the board of award. He was under consideration for the medal at the time of his death, April 19, 1939. The award, the highest distinction bestowed jointly by the four national societies of civil, mining and metallurgical, mechanical, and electrical engineers, for notable scientific and industrial achievement, went to Doctor Hirshfeld "for notable leadership through research and development in power generation and electric traction, and for being a great teacher and friend of men both old and young."

Doctor Hirshfeld was chief of the department of research of the Detroit Edison Company, Detroit, Mich. A biographical sketch and obituary notice appeared in the May issue, page 229.

Award of the John Fritz Medal is made not oftener than once a year, without restriction on account of nationality or sex. Each participating society has four representatives on the board of award. AIEE members of the present board, all past-presidents, are: J. B. Whitehead (A'00, F'13), A. M. MacCutcheon (A'12, F'26), W. H. Harrison (A'20, F'31), and John C. Parker (A'04, F'12).

W. F. Davidson Heads NRC Insulation Conference

At its 12th annual meeting, held November 2–4, 1939, at Harvard University, Cambridge, Mass., the National Research Council's conference on electrical insulation took on a new pilot—Ward F. Davidson (A'14, F'26) director of research for the Consolidated Edison Company of New York and chairman of the AIEE committee on research. Originally organized in 1928 as the NRC committee on electrical insulation, the conference with two exceptions has been operating continuously under the stimulating leadership of its retiring chairman, Doctor John B. Whitehead (A'00, F'12) director of The Johns Hopkins University school of engineering. The exceptions noted were the period (1933–34) of Doctor Whitehead's presidency of the AIEE, and the last half of the current year. A serious illness in the Spring of 1939 and an off-expressed belief in the desirability of having "new blood," caused Doctor Whitehead to insist upon the acceptance of his resignation from the chairmanship. During these interim periods, the responsibilities of leadership fell upon and were assumed by Vice-Chairman William A. Del Mar (A'06, F'20) chief engineer of the Habirshaw Cable and Wire Division of the Phelps Dodge Copper Products Corporation and long-time active participant in AIEE affairs.

At its annual dinner meeting November 3, the conference adopted by acclaim a citation paying fitting tribute to retiring Chairman Whitehead for his years of devoted service. The citation follows:

> "The conference on electrical insulation now holding its 12th annual meeting, finds itself to be an organization without parallel in the field of science and engineering. Nowhere else do we find a group of research men meeting to discuss informally work in progress in their respective laboratories. The atmosphere of mutual trust and enthusiastic co-operation is unique not only in this country but, as far as we know, in the world.
>
> "Where such a phenomenon occurs in any field, its existence is traceable to a rare personality. In this case the personality is that of our beloved retiring chairman, Doctor J. B. Whitehead.
>
> "The conference extends its appreciation and thanks for the spirit that Doctor Whitehead has infused into the conference, and for the immense amount of labor he has devoted to its successful development since its inception. May he continue to be an active member for the years to come."

In his brief response, Doctor Whitehead insisted that the evergrowing success of the conference's work should be attributed to the effective co-operation of the many participants.

With the new appointments and holdover officers, the executive committee of the conference now is constituted as follows:

W. F. Davidson, Consolidated Edison Company, New York, N. Y., chairman

S. O. Morgan, Bell Telephone Laboratories, New York, vice-chairman

Thorstein Larsen, Consolidated Edison Company, New York, secretary

H. H. Race, General Electric Company, Schenectady, N. Y., chairman, committee on physics

Arthur von Hipple, Massachusetts Institute of Technology, Cambridge, vice-chairman, committee on physics

E. L. Miller, Esso Laboratories, Elizabeth, N. J., chairman, committee on chemistry

R. N. Evans, Consolidated Edison Company, New York, vice-chairman, committee on chemistry

C. F. Hill, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa., chairman, committee on monographs

C. L. Dawes, Harvard University, Cambridge, Mass.

W. A. Del Mar, Phelps Dodge Copper Products Corporation, Yonkers, N. Y.

J. B. Whitehead, The Johns Hopkins University, Baltimore, Md.

Pursuing its customary procedure, the conference at its Cambridge sessions accommodated some two dozen informal presentations of the general nature of progress reports reflecting for the most part the status of current research in what appears to be an ever-widening field directly contributory to better electrical insulating materials and a better understanding of them. A comprehensive report reflecting the highlights of the reports presented is in preparation and scheduled for inclusion in an early issue of Electrical Engineering.

Registered attendance at the Cambridge sessions was 131.

Technological Institute At Northwestern

Classes began this fall in the new Technological Institute established at Northwestern University, Evanston, Ill., by a $6,735,000 gift from the Walter P. Murphy Foundation, Chicago. The Institute, which will train a student body of 800 in civil, mechanical, electrical, and chemical engineering, is headed by Dean Ovid W. Eshbach (A'17, F'37), and will be housed in a new building, to be begun early in 1940. The engineering faculty of the University has been increased to take care of the Institute students. Courses, which are on a five-year basis, are arranged on the co-operative plan of engineering education developed by the late Dean Herman Schneider at the University of Cincinnati, under which students will devote alternate quarters of their second, third, and fourth years to classes and to field jobs in co-operating industries. The class of 100 freshmen that entered the Institute at the beginning of the 1939–40 term represents a selected group, 73 per cent of which ranked in the upper quarter of their high-school classes. Dean R. C. Disque (M'20) of the school of engineering, Drexel Institute of Technology, Philadelphia, Pa., is acting as educational consultant for Northwestern's new Institute.

The building that is to house the Institute will be the largest on the Northwestern campus, and will contain the chemistry and physics departments of the University, as well as the engineering departments. It is expected to be ready for classes by September 1941. The building, which will cost $4,920,000, will require 4,564,290 man-hours of work in shop and field, in 32 industries, according to estimates.

Engineering School Anniversary at Columbia

With a variety of activities, including a three-day open house at scientific and engineering laboratories, demonstrations of recent developments in research and instruction, a series of lectures on strategic minerals, dedication of a memorial plaque, and awards of medals, the school of engineering of Columbia University, New York, N. Y., during November brought to a close a ten-month celebration of its 75th anniversary.

Development of the Columbia school of engineering began with the establishment in 1864 of the school of mines, said to be the first in the United States. Provision for civil engineering was made in 1868, and courses in metallurgical, electrical, mechanical, chemical, and industrial engineering and in mineral dressing were established later. The departments which conduct these courses now constitute the school of engineering.

List of Undergraduate Curricula Accredited by ECPD as of October 20, 1939

(Subject to continual revision. For basis of accrediting see ELECTRICAL ENGINEERING, December 1938, page 515; for report of ECPD seventh annual meeting, see November 1939 issue, page 485.)

University of Alabama: Aeronautical, civil, electrical, industrial, mechanical, mining

Alabama Polytechnic Institute: Electrical, mechanical

University of Arizona: Civil, electrical, mechanical, mining

University of Arkansas: Civil, electrical, mechanical

Armour Institute of Technology: Chemical, civil, electrical, mechanical

Brooklyn Polytechnic Institute: Chemical (day and 8-year evening), civil (*a*), electrical (*a*), mechanical (*a*)

Brown University: Civil, electrical, mechanical

Bucknell University: Civil, electrical, mechanical

University of California: Civil, electrical, mechanical, metallurgical (metallurgy), mining, petroleum

California Institute of Technology: Aeronautical (6-year course), chemical (5-year course), civil, electrical, mechanical

Carnegie Institute of Technology: Chemical, civil (*a*), electrical (*a*), industrial (management) (*a*), mechanical (*a*), metallurgical (*a*)

Case School of Applied Science: Chemical, civil, electrical, mechanical, metallurgical

Catholic University of America: Aeronautical, architectural, civil, electrical, mechanical

University of Cincinnati: Aeronautical, chemical, civil, electrical, mechanical

The Citadel: Civil

Clarkson College of Technology: Chemical, civil, electrical, mechanical

Clemson Agricultural College: Civil, electrical, mechanical

College of the City of New York (*a*): Civil, electrical, mechanical

University of Colorado: Architectural, civil, electrical, mechanical

Colorado School of Mines: Geological, metallurgical, mining, petroleum

Colorado State College: Civil, electrical, mechanical

Columbia University (*b*): Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

Cooper Union Institute of Technology (*c*): Civil, electrical, mechanical

Cornell University: Chemical, civil, electrical, industrial (administrative), mechanical

Dartmouth College: Civil

University of Delaware: Civil, electrical, mechanical

University of Detroit: Aeronautical, architectural, civil, electrical, mechanical

Drexel Institute: Chemical, civil, electrical, mechanical

Duke University: Civil, electrical, mechanical

University of Florida: Civil, electrical, industrial, mechanical

Georgia School of Technology: Aeronautical, chemical (excluding co-operative curriculum), civil, electrical, mechanical

Harvard University (*d*): Civil, communication, electrical, industrial (engineering and business administration), mechanical, metallurgical (physical metallurgy), sanitary

University of Idaho: Civil, electrical, mechanical, metallurgical (metallurgy), mining

University of Illinois: Architectural, ceramic (technical option), chemical, civil, railway civil, electrical, railway electrical, general (*e*), mechanical, railway mechanical, metallurgical, mining

Iowa State College: Agricultural, architectural, chemical, civil, electrical, general (*e*), mechanical

State University of Iowa: Chemical, civil, electrical, mechanical

Johns Hopkins University: Civil, electrical, mechanical

University of Kansas: Architectural, civil, electrical, mechanical, mining

Kansas Stage College: Agricultural architectural, civil, electrical, mechanical

University of Kentucky: Civil, metallurgical, mining

Lafayette College: Civil, electrical, industrial (administrative), mechanical, metallurgical, mining

Lehigh University: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

Louisiana State University: Chemical, civil, electrical, mechanical, petroleum

University of Louisville: Chemical, civil, electrical, mechanical

U niversity of Maine: Civil, electrical general (*e*), mechanical

Marquette University: Civil, electrical, mechanical

University of Maryland: Civil, electrical, mechanical

Massachusetts Institute of Technology: Aeronautical, building engineering and construction, chemical, civil, electrical, electrochemical, general (*e*), industrial (business and engineering administration), mechanical, metallurgical (metallurgy), mining, naval architecture and marine engineering (including marine transportation), public health, sanitary

University of Michigan: Aeronautical, chemical, civil, electrical, engineering mechanics, mechanical, metallurgical, naval architecture and marine engineering, transportation

Michigan College of Mining and Technology: Civil, electrical, mechanical, metallurgical, mining

Michigan State College: Civil, electrical, mechanical

University of Minnesota: Aeronautical, chemical, civil, electrical, mechanical, metallurgical, mining, petroleum

University of Missouri: Civil, electrical, mechanical

Missouri School of Mines and Metallurgy: Ceramic, civil, electrical, metallurgical, mining (mine) (including petroleum option)

Montana School of Mines: Geological, metallurgical, mining

Montana State College: Civil, electrical, mechanical

University of Nebraska: Agricultural, architectural, civil, electrical, mechanical

University of Nevada: Electrical, mechanical, mining

University of New Hampshire: Civil, electrical, mechanical

University of New Mexico: Civil, electrical, mechanical

New Mexico State College: Civil, electrical, mechanical

New York University: Aeronautical, chemical (day and 7-year evening), civil (*a*), electrical (*a*), mechanical (*a*)

New York State College of Ceramics (at Alfred University): Ceramic

Newark College of Engineering: Civil, electrical, mechanical

North Carolina State College: Ceramic, civil, electrical, mechanical

University of North Dakota: Chemical, civil, electrical, mechanical, mining

Northeastern University: Civil, electrical, industrial, mechanical

Northwestern University: Civil, electrical, mechanical

Norwich University: Civil, electrical

Ohio State University: Ceramic, chemical, civil, electrical, industrial, mechanical, metallurgical, mining (mine)

University of Oklahoma: Architectural, civil, electrical, mechanical, petroleum (production option)

Oklahoma Agricultural and Mechanical College: Civil, electrical, industrial, mechanical

Oregon State College: Civil, electrical, mechanical

University of Pennsylvania: Chemical, civil, electrical, mechanical

Pennsylvania State College: Architectural, ceramic (ceramics), chemical, civil, electrical, electrochemical, fuel technology, industrial, mechanical, metallurgical (metallurgy), mining, petroleum and natural gas, sanitary

University of Pittsburgh: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining, petroleum

Pratt Institute: Electrical, mechanical

Princeton University: Chemical, civil, electrical, mechanical

Purdue University: Chemical, civil, electrical, mechanical

Rensselaer Polytechnic Institute: Aeronautical, chemical, civil, electrical, industrial, mechanical, metallurgical

Rhode Island State College: Civil, electrical, mechanical

Rice Institute: Civil, electrical, mechanical

University of Rochester: Mechanical

Rose Polytechnic Institute: Civil, electrical, mechanical

Rutgers University: Civil, electrical, mechanical, sanitary

University of Santa Clara: Civil, electrical, mechanical

South Dakota State College: Civil, electrical, mechanical

South Dakota State School of Mines: Civil, electrical, metallurgical, mining

University of Southern California: Petroleum

Southern Methodist University: Civil, electrical, mechanical

Stanford University: Civil, electrical, mechanical, metallurgical, mining, petroleum

Stevens Institute of Technology (*e*): General

Swarthmore College: Civil, electrical, mechanical

Syracuse University: Civil, electrical, industrial (administrative), mechanical

University of Tennessee: Chemical, civil, electrical, mechanical

University of Texas: Architectural, civil, electrical, mechanical, petroleum (petroleum production)

Agricultural and Mechanical College of Texas: Civil, electrical, mechanical, petroleum

Texas Technological College: Civil, electrical, mechanical

Tufts College: Civil, electrical, mechanical

Tulane University of Louisiana: Civil, electrical, mechanical

University of Tulsa: Petroleum (including options in refining and production)

Union College: Civil, electrical

United States Coast Guard Academy (*e*): General

University of Utah: Civil, electrical, mechanical, metallurgical, mining

Utah State Agricultural College: Civil

Vanderbilt University: Civil, electrical, mechanical

University of Vermont: Electrical

University of Virginia: Civil, electrical, mechanical

Virginia Military Institute: Civil, electrical

Virginia Polytechnic Institute: Ceramic, chemical, civil, electrical, industrial, mechanical

Washington University: Architectural, civil, electrical, industrial (administrative), mechanical

University of Washington: Aeronautical, ceramic, chemical, civil, electrical, mechanical, metallurgical, mining

State College of Washington: Architectural, civil, electrical (basic and hydroelectric options), mechanical (basic option), metallurgical, mining

Webb Institute of Naval Architecture: Naval architecture and marine engineering

West Virginia University: Civil, electrical, mechanical, mining

University of Wisconsin: Chemical, civil, electrical, mechanical, metallurgical, mining

Worcester Polytechnic Institute: Civil, electrical, mechanical

Yale University: Chemical, civil, electrical, mechanical, metallurgical (metallurgy)

(*a*). Accrediting applies to both the day and evening curricula.

(*b*). Accrediting applies to the 4-year and 5-year curricula leading to the bachelor of science degree.

(*c*). Accrediting applies to day curriculum only. Action on evening curriculum deferred pending granting of degrees.

(*d*). Accrediting applies only to curriculum as submitted to ECPD and upon completion of which a certificate is issued by Harvard University certifying that the student has pursued such a curriculum.

(*e*). The accrediting of a curriculum in general engineering implies satisfactory training in engineering sciences and in the basic subjects pertaining to several fields of engineering; it does not imply the accrediting, as separate curricula, of those component portions of the curriculum such as civil, mechanical, or electrical engineering that are usually offered as complete professional curricula leading to degrees in these particular fields.

Future Meetings of Other Societies

American Association for the Advancement of Science. Winter meeting, December 27, 1939–January 2, 1940, Columbus, Ohio.

American Institute of Mining and Metallurgical Engineers. 152d annual meeting, February 12–15, 1940, New York, N. Y.

American Physical Society. Annual meeting (232d), December 28–30, Columbus, Ohio.

233d meeting, February 22–24, 1940, New York, N. Y.

American Society of Civil Engineers. Annual meeting, January 17–20, 1940, New York, N. Y.

American Society of Heating and Ventilating Engineers. 46th annual meeting, January 22–26, 1940, Cleveland, Ohio.

American Society of Refrigerating Engineers. Annual meeting, January 17–19, 1940, Chicago, Ill.

Louisiana Engineering Society. Annual meeting, January 12–13, 1940. New Orleans, La.

Society of Automotive Engineers. Annual meeting, January 15–19, 1940, Detroit, Mich.

New Engineering Degree to Be Given at NYU

The degree of doctor of engineering science will be conferred by the graduate division of the New York University College of Engineering, New York, N. Y., at the close of the academic year 1939–40. The new degree, the first of its type to be offered by an accredited engineering school in the United States, is approved by the Council of the University and the New York State Board of Regents.

A co-operative plan for graduate instruction in electrical engineering in which New York University, Brooklyn Polytechnic Institute, Brooklyn, N. Y., Stevens Institute of Technology, Hoboken, N. J., and the educational division of Westinghouse Electric and Manufacturing Company, New York, will participate, has also been announced. This is the first such program of graduate study to be put into practice in the New York City area.

Illinois Institute of Technology. Armour Institute of Technology, and Lewis Institute, both in Chicago, Ill., are to be consolidated into a new and larger institution, following an agreement by the trustees of the two schools. The new school will be known as Illinois Institute of Technology, and the names of the two component schools will be retained for its two divisions. Actual consolidation of the educational program will be complete by September 1940. For the present, the buildings and equipment of both Armour and Lewis will be used. A board of 55 trustees, made up of the present trustees of both, will govern the new institution, which will have an enrollment of about 7,000 day and evening students.

Vermilye Medal Established by Franklin Institute

The Franklin Institute has awarded the first Vermilye Medal, presented "in recognition of outstanding contribution in the field of industrial management," to Lewis H. Brown, president, Johns-Manville Corporation, New York, N. Y. The medal, named for its donor, W. M. Vermilye, vice-president, National City Bank of New York, will be awarded biennially or at longer intervals by the Franklin Institute, on recommendation of a committee of board members and an advisory committee including engineers and industrialists and representatives of The American Society of Mechanical Engineers, the Chamber of Commerce of the United States, and the National Association of Manufacturers. The last-named is represented by J. W. O'Leary (A'18) chairman of the board, Arthur J. O'Leary and Son Company, Chicago, Ill.

The presentation to Mr. Brown, "for his brilliant work in executive management in industry," was made at Philadelphia, Pa., November 14, 1939.

Fifty Years of Meters Commemorated by G.E.

Fifty years of manufacturing watt-hour meters at the West Lynn, Mass., plant of the General Electric Company was celebrated October 4, 1939, with a program at the Lynn municipal stadium, open house at the plant, a commemorative dinner, and other events. The 20,000,000th G.E. watt-hour meter was presented to Alex Dow (A'93, F'13, HM'37) president of the Detroit Edison Company, Detroit, Mich., who was chairman in 1898 of the original meter committee of the Association of Edison Illuminating Companies.

The Thomson-Houston Electric Company, one of the predecessors of General Electric, began in 1889 to manufacture the watt-hour meter developed by Elihu Thomson (A'84, F'13, HM'28) co-founder of the company. In fundamentals, this type of instrument has not been materially changed since it was sent by Thomson to the Paris Exposition where it divided first prize. It has long been the standard meter manufactured by General Electric for all d-c uses, though superseded for a-c use by the induction wattmeter.

New Boulder Dam Generator. The eighth generator of 82,500-kva capacity has gone into operation at Boulder Dam, serving the Southern California Edison Company, Ltd. The new unit is the third generator operating in the Arizona wing of the powerhouse. Another large generator and a small one were already in operation on that side, and six large ones on the Nevada side. Like its immediate predecessor, installation of which was noted in the October issue, page 438, the new unit was hurried to completion to meet a power shortage resulting from insufficient rain. It brings the installation to about half its final capacity.

Thurston Book Reissued by Cornell

"A History of the Growth of the Steam-Engine," has been reissued in a "centennial edition" by Cornell University, in connection with its centennial celebration of the birth of the author, Robert H. Thurston, who was director of the Sibley College of Mechanical Engineering at Cornell University from 1885 to 1903. A prefatory statement prepared by Professor William N. Barnard, present director of the Sibley School of Mechanical Engineering at Cornell University, calls attention to the fact that Doctor Thurston's original book issued in 1878:

> "Met the need for such a work in so satisfactory a manner that the book passed through six editions, the last published in 1907 with an additional chapter. Even now, despite the appearance of later books on the same subject by other authors, his presentation is considered a classic for the period of history covered, and there is still considerable demand for it, with but few copies readily accessible. Accordingly, it seems in every way appropriate to issue a new edition of this work, and to do so in connection with the one hundredth anniversary of the author's birth, celebrated at Cornell on October 25, 1939."

Inasmuch as Doctor Thurston's own story ends with the last century, a supplementary chapter by Professer Barnard has been added to the centennial edition, tracing some of the more important developments in steam-power engineering since that time. Copies of the centennial edition, containing 555 $5^{1}/_{2}$-by-8-inch pages, may be procured from the Cornell University Press, 124 Roberts Place, Ithaca, N. Y., at $3.00 each.

New ASME Officers. New officers of The American Society of Mechanical Engineers, installed at the annual meeting of the society, Philadelphia, Pa., December 4–8, 1939, are: *president*—W. H. McBryde, San Francisco, Calif.; *vice-presidents*—K. H. Condit, New York, N. Y., Francis Hodgkinson (A'02), New York, N. Y., J. C. Hunsaker, Cambridge, Mass., K. M. Irwin, Philadelphia, Pa.; *managers*—J. W. Eshelman, Birmingham, Ala., Linn Helander, Manhattan, Kans., G. T. Shoemaker (M'20), Chicago, Ill.

"Results of Municipal Lighting Plants," sixth edition has just been issued by Burns and McDonnell Engineering Company of Kansas City, Mo.; price, $5.00. Flexibly bound and containing 380 pages, including several charts and graphs, this book is introduced as presenting the latest available information from 717 municipal lighting plants, in the United States, Canada, Alaska, and the Philippines, concerning rates, earnings, cost of production, revenues, and other pertinent information.

Fifty-Year Employees Honored. Allis-Chalmers Manufacturing Company, Milwaukee, Wis., recently honored 38 men employed by the company 50 or more years by issuing a booklet "We've Gone Places Together," which contained photographs and biographies of the 50-year men. Copies of the booklet, and gold watches, were presented to the men at a dinner in their honor September 23, 1939.

NAM to Honor Modern American Pioneers

"Modern Pioneers," defined as the inventors who have contributed most to the American standard of living during the past 25 years, will be honored by the National Association of Manufacturers at a celebration commemorating the 150th anniversary of the establishment of the United States patent system. A committee of six scientists, of which Doctor K. T. Compton (F'31) president of Massachusetts Institute of Technology, Cambridge, is chairman, has been chosen to select the inventors and scientists. Those named will be presented with awards at a dinner to be held in New York, N. Y., February 27, 1940, and previously honored in their own communities.

A committee of 80 industrialists, headed by Robert L. Lund, executive vice-president, Lambert Pharmacal Company, and chairman, patents and trademarks committee, NAM, has been appointed to promote the search for outstanding inventors. Committee members include W. S. Gifford (A'16) president, American Telephone and Telegraph Company; and David Sarnoff (M'23) president, Radio Corporation of America. Manufacturers, trade groups, and scientific organizations have been asked to nominate persons for distinction as "Modern Pioneers."

Medals Awarded by Society of Chemical Industry

The Chemical Industry Medal, awarded annually for valuable application of chemical research to industry, has been presented this year to Doctor Robert E. Wilson, president, Pan-American Petroleum and Transport Company. The award was made November 10, 1939, at a joint meeting of the American Section of the Society of Chemical Industry, the New York Section of the American Chemical Society, and the New York Section of the American Institute of Chemical Engineers.

The Perkin Medal of the Society of Chemical Industry has been awarded for 1940 to Doctor Charles M. A. Stine, vice-president in charge of research, E. I. du Pont de Nemours and Company, Wilmington, Del. The award, given annually for valuable work in applied chemistry, is made by a committee representing the five chemical societies in the United States. It will be presented to Doctor Stine at a meeting to be held in New York, N. Y., January 12, 1940.

Electrical Insulating Materials. The 1939 edition of ASTM Standards on Electrical Insulating Materials, recently issued, contains specifications and tests on insulating varnishes and related products; molded materials; plates, tubes, and rods; insulating oils; glass; rubber products; asbestos yarns, and other products. Standarized procedures for electrical tests are included. Copies of the paper-covered 320-page publication may be obtained from the American Society for Testing Materials, 260 Broad Street, Philadelphia, Pa., at $2.00 per copy.

Texas Dam Project. Marshall Ford Dam on the Colorado River of Texas near Austin will be increased in height by 78 feet, to a total of 270 feet, in accordance with plans for the second stage of this development as approved by the last Congress. Under construction by the United States Bureau of Reclamation, the project is intended for flood control, power, and river regulation for navigation purposes. The power plant is scheduled to be built as part of the second-stage development, and is planned to accommodate three 20,000-kw units.

Lamme Graduate Scholarship Awarded. The Benjamin Garver Lamme Graduate Scholarship, awarded annually by the Westinghouse Electric and Manufacturing Company to one of the young engineers employed by the company, has been presented for the year 1939–40 to G. W. Jernstadt, chemical engineer in the meter division of the company at Newark, N. J. He will use the scholarship, which provides $1,500 for advanced study, for research on beryllium electroplating of copper.

Current Items From American Engineering Council

Committee Hears Criticism of Civil Service

Many suggestions for the improvement of the Federal civil service were presented at a public hearing held November 1 and 2 in Washington by the President's Committee on Merit System Improvement, which is now preparing a report that is expected to recommend the inclusion of higher grades of professional employees within the classified civil-service system, as well as other changes.

The committee, which is headed by Supreme Court Justice Stanley Reed, includes in its membership Gano Dunn (A'91, F'12) and General Robert E. Wood as representatives of the engineering professions and of business, respectively, as well as a number of high government officials. It was formed by President Roosevelt last February and has been studying the problem since that time. The submission of a final report is anticipated in the near future.

Of the many persons who presented testimony at the hearing only one, General Counsel D. W. Robinson, Jr., of the Federal Power Commission, opposed the further extension of the merit system. It was Mr. Robinson's contention that because of the peculiar requirements of his agency it could do a better job of selecting its legal staff than could the Civil Service Commission. All other witnesses supported the merit system in principle, but most of them submitted specific criticisms of the manner in which it is now functioning, and some recommended material modification of its procedure in recruiting employees for the more responsible positions. A representative of the Department of Agriculture, for example, suggested that its scientists and other experts be selected by joint boards made up from the Civil Service Commission, the Department itself, and one or more outside experts in the specific field involved.

Complaints directed at the administration of the present system may be briefly summarized as follows: Its examinations and lists are too general; too much time is consumed in the preparation of examinations, grading, and the compilation of eligible lists; registers are frequently too old; classification of jobs looks more to the number of subordinates controlled than to the real responsibilities of the position; present promotion and transfer procedure is inadequate; more attention should be paid to the training of employees for promotion. (Those who attended AEC's annual assembly last January will remember that at that time a representative of the Civil Service Commission recognized the validity of similar criticisms, but contended that their remedy was largely in the provision of more personnel and funds.)

Provisions of basic civil-service law that came in for criticism included the state quota system and the preference granted to war veterans in grading applicants.

Plan Pan-American Scientific Meeting

Preliminary plans for the eighth American Scientific Congress, to be held in Washington May 10–14, 1940, have been announced by the Department of State, following the dispatch of invitations to participate to the governments of all American republics affiliated with the Pan-American Union. An organizing committee has already been named, headed by Under-Secretary of State Sumner Welles and composed of heads of a number of scientific and governmental bodies, including Doctor C. G. Abbot and Doctor Alexander Wetmore, Smithsonian Institution; Doctor Isaiah Bowman, Johns Hopkins University; Doctor Vannevar Bush (A'15, F'24) Carnegie Institution; Doctor Ross G. Harrison, National Research Council; Doctor James Brown Scott, Carnegie Endowment for International Peace; and Doctor Leo S. Rowe, Pan-American Union.

At a recent meeting of this organizing committee it was decided to divide the congress into eleven sections, each to be in charge of a chairman to be assisted by a vice-chairman and a section committee, which will soon be selected. The sections will cover, respectively, the anthropological sciences; the biological sciences; the geological sciences; agriculture and conservation; public health and medicine; physical and chemical sciences; statistics, history, and geography; international law, public law, and jurisprudence; economics and sociology; and education.

Standards

Trends in AIEE Standards Work

In recent years there have been two important trends affecting the work of the Institute on standards for electrical apparatus. These trends are discussed in the article that follows by R. E. Hellmund, chairman, AIEE standards committee, and P. L. Alger, chairman, co-ordinating committee 4.

On one hand, the broadening commercial interest in standards requires the participation and approval of a continually increasing number of persons in the development of any particular standard. To meet this, the American Standards Association has developed the system of Sectional Committees, with representation from all interested suppliers and users, and also from the public, who must give final approval to American standards. The Institute may serve as a sponsor in the preparation of an electrical standard, but usually there are other groups which have an active interest also. The continually increasing variety of electrical products and the diversity of their characteristics and applications require a corresponding increase in the number of specific standards to serve the industry.

These trends have changed the character of the Institute work on standards, but have by no means decreased its importance. The broad objective of the Institute in this field remains as before—that of giving effective service to the electrical industry, promoting clarity of understanding, adequate measurements of performance, and guidance toward the minimum variety of standards having the maximum uniformity between them consistent with progress.

Under present-day conditions, there are four specific objectives toward which the standards activities of the Institute are especially directed:

(1) There is the very important purpose of supplying essential basic facts and technical information necessary for establishing proper numerical values for standard temperatures, voltages, torques, and other characteristics that must be fixed in commercial standards. Similarly, various methods of test must be explained and discussed so that the best procedure may be decided upon for conducting guarantee tests or giving other proofs of performance. Gathering and presenting technical information to the electrical industry through the medium of Electrical Engineering and the various Institute conventions is, of course, the prime purpose of the Institute's existence. While the connection between many Institute papers and standards appears remote, it is nevertheless true that nearly all technical papers recorded in the Transactions have in some degree an influence on the standards adopted by the industry. Examples of recent papers of particular importance in this field are those given at the Symposium on Rating of Electrical Apparatus conducted at the 1939 winter convention, the supplementary paper on Ambient Temperature presented at the combined summer and Pacific Coast convention at San Francisco, and the very recent papers presented at the standards session of the Middle Eastern District meeting at Scranton, Pa. Other activities of the Institute relating to standards are the development of the several Institute test codes, and the series of technical conferences held at recent conventions to discuss such codes.

(2) The Institute performs an important service in supplying definitions of electrical terms and other educational material and in promoting understanding of tests and other procedures involved in the application of standards in particular cases. Even though a standard may be clearly written and its application in normal cases may be noncontroversial, there frequently arise border-line cases in which the underlying thought or objectives held in view by those who compiled the standard should be understood for its proper interpretation. By committee reports and explanatory articles frequently prefacing a standard or recorded during its compilation, the Institute provides a helpful clarification of ideas.

(3) Another function of the Institute, which seems of increasing importance under present conditions, is that of providing guidance in the development of new standards. The multiplicity of standards now required gives rise to many cases of overlapping or conflicting rules as well as to unnecessary multiplicity of numerical values and other limits which must be complied with. By the development of general principles and of preferred numerical values that can be followed by individuals in widely different fields who compile standards for specific types of apparatus, the co-ordination of types of apparatus to be associated is greatly facilitated. For example, the associated use of transformers, lightning arresters, circuit breakers, bushings, and insulators on high-voltage systems requires that reasonably consistent insulation levels be adhered to in all components of the system, and this in turn requires that the impulse test values and other insulation requirements be co-ordinated in the various specific standards.

Likewise, without such general guiding principles, a great many more numerical values of standard voltages, standard temperature limits, and other characteristics would be specified than are at all necessary for adequate service to the industry. An example of the Institute's work in this field is the revision of AIEE Standard No. 1 now being carried on under the auspices of the standards committee. Similarly, work is being done on the simplification and co-ordination of insulation tests, the lining-up of standard reference temperatures, and other matters, with a view to promoting the maximum consistency between American and international standards, as well as among the Institute standards themselves.

Under present world conditions, it is especially important that further study be given to correlation of the IEC and American standards in view of the increasing foreign demand for American apparatus and the necessity for co-ordinating it with existing systems built up on the basis of IEC rules.

(4) Besides these services in the way of supplying facts, definitions, guiding principles, and educational material, all of which must precede and underlie the development of sound standards, the Institute acts as sole or joint sponsor, under the ASA rules, for the development of many specific standards in the electrical field. Throughout the electrical field, the Institute has every right, and an obligation, to propose new or improved standards, and the technical sessions of the Institute should serve as a proving ground for testing the worth of all new ideas along these lines. Of course all such standards developed or proposed by the Institute must go through the ASA Sectional Committee procedure and win the approval of the other interested groups before final adoption, and these other groups will introduce additional features in the standards, particularly with reference to standard sizes, speeds, characteristics, and other subjects of primary commercial importance. However, the Institute's part in providing fundamental knowledge and technically sound procedures will always remain a vital element in standards development.

Commercial standards developed through the ASA procedure are often a long time being completed and usually remain in force for extended periods. Furthermore, changes in such standards usually should consist in modifications rather than revolutionary alterations, as otherwise the stability necessary for commercial progress cannot be obtained. On the other hand, the Institute publications on its standards, especially those dealing with guiding principles, improved test methods, and other matters which should be considered whenever changes in the more commercial standards are timely, should flow in a continuous stream, with frequent revisions and additions, so as to be up to date at all times. By thus keeping available in convenient reference form a complete set of facts and principles for the guidance of those responsible for the preparation of commercial standards, the Institute can render a most important service to the industry.

United Engineering Trustees, Inc.

Joint Organizations of the Engineering Societies

United Engineering Trustees, Inc., one of the joint agencies supported and participated in by the AIEE, was organized in 1904 as an instrumentality of the four national societies of civil, mining and metallurgical, mechanical, and electrical engineers. Its purpose is the management of property and funds in which these societies have joint interests, and it is governed by trustees duly appointed by the societies as their representatives. It maintains two departments: the Engineering Societies Library, and The Engineering Foundation.

The corporation (UET, Inc.) manages the Engineering Societies Building and all trust funds placed in the hands of UET, Inc.

The Engineering Societies Library is a free public engineering library, which is operated for users at a distance, as well as for those who visit its rooms in the Engineering Societies Building.

The Engineering Foundation, founded by the late Ambrose Swasey in 1914, is entrusted with the expenditure of income from endowment and other funds. The ultimate objective of the Foundation is stated to be: "the furtherance of research in science and engineering, or for the advancement in any other manner of the good of the profession of engineering and the good of mankind."

In the accompanying articles may be found announcements of the elections recently held by UET and The Engineering Foundation, and abstracts of the annual reports of these organizations and of the Engineering Societies Library.

Election of Officers of United Engineering Trustees, Inc.

Officers to serve the United Engineering Trustees, Inc., for the year 1939–40 were elected at the recent annual meeting of UET. H. A. Lardner (A'94, F'13) was elected president. J. P. H. Perry was elected vice-president, and Albert Roberts re-elected vice-president. H. R. Woodrow (A'12, F'23) was re-elected treasurer; W. D. B. Motter, Jr., was elected assistant treasurer; and John H. R. Arms was re-elected secretary and general manager. The first five constitute the executive committee.

Members of the board of trustees of UET for the year 1939–40, including both new and holdover members, with the societies they represent, are:

Terms expiring October 1940
Otis E. Hovey, ASCE
W. D. B. Motter, Jr., AIME
Kenneth H. Condit, ASME
H. R. Woodrow (A'12, F'23), AIEE

Terms expiring October 1941
A. L. Queneau, AIME
F. M. Farmer (A'02, F'13, president), AIEE

Terms expiring October 1942
J. P. H. Perry, ASCE
H. A. Lardner, ASME

Terms expiring October 1943
J. P. Hogan (M'31), ASCE
Albert Roberts, AIME
D. Robert Yarnall, ASME
C. E. Stephens (M'22), AIEE

Of these C. E. Stephens is newly appointed; J. P. Hogan, Albert Roberts, and D. Robert Yarnall are reappointed; all others were held over.

Newly appointed to the finance committee are Otis E. Hovey and C. E. Stephens; reappointed, Albert Roberts, *chairman*, and H. R. Woodrow. C. E. Stephens was appointed to the real estate committee; J. P. H. Perry, chairman, A. L. Queneau, and Kenneth H. Condit were reappointed. H. A. Lardner is a member ex officio of both committees.

Engineering Societies Library Officers and Board Elected

At the recent annual meeting of United Engineering Trustees the following officers were appointed or reappointed to the board of the Engineering Societies Library: A. R. Mumford, chairman; J. W. Laist, vice-chairman; Harrison W. Craver, director. Mr. Craver is also secretary, ex-officio.

Members of the Library board appointed or reappointed for 1939–40, with the societies they represent, are:

Terms expiring October 1940
C. E. Trout, ASCE
J. W. Laist, AIME
A. R. Mumford, ASME
W. A. Del Mar (A'06, F'20), AIEE
A. W. Berresford (A'94, F'14, past-president), member-at-large

Terms expiring October 1941
J. K. Finch, ASCE
F. F. Sharpless, AIME
John Blizard, ASME
W. I. Slichter (A'00, F'12), AIEE
S. H. Ball, member-at-large

Terms expiring October 1942
J. J. Yates, ASCE
Thomas T. Read, AIME
W. E. Spear, member-at-large

Terms expiring October 1943
E. E. Church, Jr., ASME
W. S. Barstow (A'94, F'12), AIEE
W. D. B. Motter, Jr., UET board of trustees

Ex officio
G. T. Seabury, secretary, ASCE
A. B. Parsons, secretary, AIME
C. E. Davies, secretary, ASME
H. H. Henline, national secretary, AIEE
Harrison W. Craver, director, Engineering Societies Library

Members of the executive committee for 1939–40 are:

W. S. Barstow
J. K. Finch
W. D. B. Motter, Jr.
W. I. Slichter

Engineering Foundation Elects Officers

At the recent annual meeting of The Engineering Foundation, G. E. Beggs was elected chairman for 1939–40, and O. E. Buckley (M'19, F'29) was elected vice-chairman. These two, with F. F. Colcord, Kenneth H. Condit, and A. L. Queneau, comprise the executive committee. Other re-elections were O. E. Hovey, director, and John H. R. Arms, secretary.

The officers and executive committee are elected by The Engineering Foundation board from among its own members. The board is itself elected by the board of trustees of UET, Inc. Complete list of its members for 1939–40, with the societies each represents and the time at which each term expires, is as follows:

Four Trustees of UET, Inc.		
A. L. Queneau	AIME	1941
Kenneth H. Condit	ASME	1943
O. E. Hovey	ASCE	1941
H. R. Woodrow	AIEE	1943
Eight Members Nominated by Founder Societies		
G. D. Barron	AIME	1940
G. E. Beggs	ASCE	1943
F. F. Colcord.	AIME	1942
F. M. Farmer	AIEE	1943
W. H. Fulweiler	ASME	1940
A. A. Potter	ASME	1943
E. M. T. Ryder	ASCE	1942
W. I. Slichter	AIEE	1940
Three Members-at-Large		
O. E. Buckley	AIEE	1942
J. V. N. Dorr	AIME	1943
E. R. Fish	ASME	1943
President of UET, Inc., ex officio		
H. A. Lardner	ASME	

Members of the research procedure committee, as appointed or reappointed, with the societies they represent, are:

O. E. Buckley, The Engineering Foundation.

K. H. Condit, The Engineering Foundation.

L. W. Chubb (A'09, F'21, past director) director, research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., AIEE.

W. H. Fulweiler, Philadelphia, Pa., ASME.

Sam Tour, Lucius Pitkin, Inc., New York, N. Y., AIME.

H. E. Wessman, New York University, New York, N. Y., ASCE.

G. E. Beggs, ex officio.

The personnel of other committees as appointed or reappointed at this meeting is as follows:

IRON ALLOYS

G. B. Waterhouse, *chairman*, professor of metallurgy, Massachusetts Institute of Technology, Cambridge, Mass., representing AIME.

Lyman J. Briggs, director, National Bureau of Standards, represented by J. G. Thompson, chief of section on chemical metallurgy, National Bureau of Standards, Washington, D. C.

J. W. Finch, director, United States Bureau of Mines, represented by R. S. Dean, chief engineer, Metallurgical Division, Washington, D. C.

J. T. MacKenzie, metallurgist and chief chemist, American Cast Iron Pipe Company, Birmingham, Ala., representing American Foundrymen's Association.

John Johnston, director of research, United States Steel Corporation, Kearny, N. J., representing American Iron and Steel Institute.

Bradley Stoughton, dean of engineering, Lehigh University, Bethlehem, Pa., representing American Society for Metals.

Jerome Strauss, vice-president, Vanadium Corporation of America, Bridgeville, Pa., representing American Society for Testing Materials.

T. H. Wickenden, metallurgical engineer, International Nickel Company, New York, N. Y., representing The Society of Automotive Engineers.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York, N. Y., representing American Electrochemical Society.

Wilfred Sykes (A'09, F'14, past manager) assistant to the president, Inland Steel Company, Chicago, Ill.; member-at-large.

F. T. Sisco, *editor*.

WELDING RESEARCH

C. A. Adams (A'94, F'13, past-president) *chairman;* consulting engineer, Edward G. Budd Manufacturing Company, Philadelphia, Pa.

H. C. Boardman, research engineer, Chicago Bridge and Iron Company, Chicago, Ill.

Everett Chapman, president, Lukenweld, Inc. Coatesville, Pa.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York N. Y.

J. J. Crowe, engineer-in-charge of apparatus, research, and development department of Air Reduction Company, Jersey City, N. J.

A. S. Douglass, construction engineer, Detroit Edison Company, Detroit, Mich.

C. L. Eksergian, chief engineer, Budd Wheel Company, Detroit, Mich.

A. J. Ely, mechanical engineer, Standard Oil Development Company, Elizabeth, N. J.

H. M. Hobart (A'94, F'12, past vice-president) consulting engineer, General Electric Company, Schenectady, N. Y.

D. S. Jacobus (A'03) advisory engineer, The Babcock and Wilcox Company, New York, N. Y.

G. F. Jenks, colonel, Ordnance Department, United States Army, Washington, D. C.

F. H. Frankland, chief engineer, American Institute of Steel Construction, New York, N. Y.

P. G. Lang, Jr., engineer of bridges, Baltimore and Ohio Railroad, Baltimore, Md.

F. T. Llewellyn, research engineer, United States Steel Corporation, New York, N. Y.

R. E. Zimmerman, vice-president, United States Steel Corporation of Delaware, Pittsburgh, Pa.

William Spraragen (A'17, M'26) *secretary*, technical secretary and editor, New York, N. Y.

Chairman Beggs was appointed Foundation's representative on the executive board of National Research Council, and O. E. Hovey reappointed representative on the highway research board.

Annual Report Issued by United Engineering Trustees, Inc.

The annual report of United Engineering Trustees, Inc., for the year ending September 30, 1939, has been submitted to the AIEE and other participating societies by D. Robert Yarnall, president.

During the year considerable study has been given to clarifying and simplifying the work of the organization, and the "History, Charter, and Bylaws" has been revised and brought up to date, as a guide to the trustees and for the information of the Founder Societies or others wishing to contribute to the work.

Summary of UET, Inc., Finance Committee Report on Funds and Property

		Book Value	Market Value
Combined Fund:* **Summary of investments September 30, 1939**			
Funds included			
Engineering Foundation fund		$ 895,849.50	
Edward Dean Adams fund		90,911.06	
Library endowment fund		168,346.55	
Depreciation and renewal fund		415,225.16	
General reserve fund		10,193.86	
Total		$1,580,526.13	
Investments			
Legal	$ 393,200.75		
Nonlegal	1,097,382.30		
Total investments September 30, 1939	1,490,583.05		
Cash uninvested	89,943.08		
Total	$1,580,526.13		$1,317,399.52
Other Funds and Property			
Real estate, cost of, September 30, 1939		$1,993,793.92	
Henry R. Towne engineering fund investments		46,040.63	25,977.21
Henry R. Towne engineering fund uninvested cash		2,592.90	
The D. Guggenheim Medal board of award investments, net		15,840.00	8,262.10
The John Fritz Medal board of award investments		3,500.00	3,482.50
UET, Inc., operating assets		10,986.05	
UET, Inc., accounts receivable, gross		1,315.39	
Engineering Societies Library maintenance assets		12,051.25	
Library Service Bureau accounts receivable, gross		980.96	
Gift for endowment committee cash		653.62	
The Engineering Foundation—unexpended income		23,884.80	
Alloys of iron research—unexpended income		7,088.30	
Welding research—unexpended income		726.05	
The Engineering Foundation custodian fund cash		6,623.44	
United Engineering Trustees, Inc., custodian funds—unexpended income		1,547.40	
Total		$3,708,150.84	

* A group of funds managed as one for convenience and economy in investment transactions.

Maintenance of the Engineering Societies building, now 33 years old, may be expected to necessitate increasing renewals. New heating system controls have been installed, improvements in ventilating the meeting halls made, and other routine maintenance carried on. The property remains tax exempt, as does the corporation. Use of meeting rooms has been provided gratuitously to federal, state, and municipal organizations for military and WPA projects and to the WPA and the New York City Board of Education for adult education classes.

Both the John Fritz Medal Fund Corporation and the Daniel Guggenheim Medal Fund, Inc., dissolved their corporations in 1939 and became committees of UET, Inc.

Operation of Engineering Societies Building

Operating revenue	$157,381.07
Less operating expenditures	158,117.77
Operating deficit	736.70
Operating credit from previous years	13,038.14
Net credit balance September 30, 1939	$ 12,301.44

Formal acceptance of responsibility for these dissolved corporations represents a change in name rather than in procedure, since the funds of the former and the books of the latter had been managed by UET, Inc., for a long period. UET, Inc., is treasurer of the Engineers Council for Professional Development, and custodian of the Engineering Societies Employment Service relief fund.

The corporation's investment advisers report that, as compared with a year ago, the total current value of its portfolio has increased slightly, and while the current return is slightly reduced, the corporation's position is considerably more liquid. Summaries of the UET finance committee's report on funds and property and on operation of the Engineering Societies building are contained in the accompanying tabulations.

Annual Report Issued by Engineering Societies Library

The annual report of the Engineering Societies Library for the year ending September 30, 1939, has been submitted to the AIEE and other participating societies by Harrison W. Craver, director.

The year was again marked by increased use and enlargement of facilities. The library had more readers than during the preceding year, made more searches, translations, and photostatic prints, and answered more requests for information. The library was used by 43,110 persons, 1,160 more than in the preceding year. Of these, 32,471 visited it in person. The remaining 10,639 were nonvisitors who were assisted in various ways. Translations were made for 113; for 2,508 of them 21,907 photoprints were made, 91 presented inquiries that necessitated extensive searches. Books to the number of 186 were lent to 162 members, information was provided to 2,985 persons by mail and 4,780 by telephone.

During the year, the collection was increased from 144,262 volumes, 7,408 maps, and 4,391 searches, to 146,999 volumes, 7,564 maps, and 4,440 searches. In addition 3,399 pamphlets were added to volumes already counted. There are also approximately 13,000 duplicate volumes on hand. Cataloging is up to date. In addition, further progress has been made in recataloging the pamphlets in the Wheeler collection of electrical books.

The work of repairing and rebinding valuable rare books, which was so generously supported by W. S. Barstow (A'94, F'12), was completed in March. In all, 1,268 volumes were repaired during the three years that this work was in progress.

Operation of Engineering Societies Library

Maintenance revenue	$45,947.94	
Maintenance expenditures	46,836.38	
Debit balance for year 1938–39	888.44	
Credit balance from previous years	6,072.23	
Credit balance September 30, 1939		$ 5,183.79
Service bureau revenue	8,512.24	
Service bureau expenditures	7,169.41	
Credit balance for year 1938–39	1,342.83	
Credit balance from previous years	6,223.56	
Credit balance September 30, 1939		7,566.39
Total net operating credit balance cumulated to September 30, 1939		$12,750.18

The periodical index now contains over 242,000 references to important periodical articles, classified by the system used for the book collection. The number of readers who consult this index is growing steadily.

Through purchase and gift the library acquired 15,914 items; 4,340 books, 11,348 pamphlets, 177 maps, and 49 searches. Of these receipts 6,491 items were suitable additions to the library. Of the remainder, 99 books (duplicates) were added to the lending collection and 9,074 items were added to the duplicate collection. Sales of duplicates during the year amounted to $384.42.

The number of periodicals received currently was 1,340. Publishers presented 627 books, for which the library staff prepared book notices which were published in the various Society journals. If purchased, these books would have cost approximately $2,000.

During the year 14,358 gifts were received. Among the donors were Mrs. Henry Alexander, G. M. Basford, F. G. Clapp, H. A. Hopf, Murray and Flood (electrical books and periodicals), the New York Society Library, and *Engineering News-Record*.

In June, the director was asked by the American Library Association to represent it at the 1939 meeting of the International Committee of the International Federation of Library Associations, held in The Hague and Amsterdam. In connection with the trip, a number of large technical libraries in Great Britain and Scandinavia were visited.

In appreciation of the various benefactions of W. S. Barstow, a dinner was tendered him on May 15, at the Lotos Club, with Gano Dunn (A'91, F'12) as toastmaster.

The budget for general operations was $49,100. Of this sum $35,959.70 was appropriated by the Founder Societies on a membership basis as follows:

American Society of Civil Engineers	$9,631.40
American Institute of Mining and Metallurgical Engineers	7,520.90
American Society of Mechanical Engineers	9,118.10
American Institute of Electrical Engineers	9,689.30

Expenditures from this budget amounted $46,836.38, of which $8,702.45 was spent for books and other equipment of permanent value. The service bureau received $8,512.24 in payment for translations, searches, and copies, and spent $7,169.41. The accompanying tabulation summarizes the year's operation of the library.

Annual Report Issued by Engineering Foundation

The annual report of The Engineering Foundation for the year ending September 30, 1939, has been submitted to the AIEE and other participating organizations by F. M. Farmer (A'02, F'13, president) chairman of the Foundation board, who was assisted by Otis E. Hovey, director.

The financial statement shown in the accompanying tabulation summarizes the present capital funds of the Foundation, and the incomes and expenditures during the year. Three additions to the capital funds were made during the year, as follows:

Sophie M. Gondron bequest	$25,000.00
Karl Emil Hilgard bequest	1,776.63
Richard Khuen, Jr., bequest	2,000.00
Total	$28,776.63

The Foundation sponsors and assists a wide range of research projects, most of them of a technical engineering character, but some dealing with non-technical matters of concern to engineers, educators, and the public. Work on 16 active projects, in 2 of which the AIEE is directly interested, has progressed during the report year. These projects included 33 specific problems. Fifteen formal applications for appropriations embodying over 30 specific problems were received, and grants were recommended for 14 of them. To establish personal contact and closer co-operation with those in charge of technical researches receiving Foundation support or assistance, the director has visited during the year four institutions and laboratories at which work is in progress. A summary of activities follows:

Soil Mechanics and Foundations Division (ASCE). The following studies are included:

Earths, Dams, and Embankments ($800). The committee has accumulated and studied data on methods used for recording static water pressure in embankments and foundations. Plans of the three most promising methods have been sent to committee members, with a view toward preparing a report upon the method, or methods, which appear to be the best.

Sampling and Testing ($5,000). The principal work of this committee continues to be the development of better methods and equipment for obtaining undisturbed samples. A report was presented to ASCE in April 1939, and will be prepared in final form at an early date.

Summary of Engineering Foundation Financial Resources

Capital Funds

Endowment, total book value September 30, 1939		$990,000.00
E. H. McHenry bequest, in hands of executors during life of two beneficiaries, appraised at probate of will in 1931, approximately		$400,000.00

The capital funds are held and administered by United Engineering Trustees, Inc. The net income from endowment was $38,838.37 for the fiscal year ended September 30, 1939. The Foundation board has discretion in use of income. For many of the enterprises which the Foundation has aided, large contributions of money, services, and materials have been obtained from others. Money "contributions" from organizations and individuals, for specific activities, passed through the Foundation's accounts from its organization to September 30, 1939, totaled $355,557.56.

Expendable Resources—Summary

Balance October 1, 1938		$29,873.42
Receipts		
Income from endowment	$38,838.37	
Income from minor items	181.11	39,019.48
Total Resources		$68,892.90

Disbursements—Summary

Research projects	$33,865.79	
Promotion of research and administrative expenses	11,142.31	
Total for furtherance and support of research		$45,008.10
Balance October 1, 1939		$23,884.80

Seepage and Erosion ($800). The committee has sponsored the continuance of model studies on earth dams, and has taken under consideration the problem of rational design of drainage filters for dams, dikes, and levees. Information on filters from tests under way is being collected and will be submitted at an early date as an interim report summarizing and correlating the results from various sources. The main objectives of the study at present are development of relatively simple grading requirements for filter materials, and development of relatively simple tests to determine the suitability of local materials for filters.

Foundations ($800). The committee has collected data and is compiling results of observations on lateral earth pressures and pressures on concrete forms. Observations on the behavior of typical "quick" sands and their mechanical and hydraulic properties are being made. Settlement observations are being made on one large new structure. Thirty-three special leveling plugs were made for this purpose and installed both inside and outside of the building at the earliest possible stage of construction, and observations of settlement are being made periodically.

Project 38-d-1 ($150). Funds granted for this year could not be used on account of the unsettled conditions in Europe. No grant was requested for the coming year.

Special Committee on Hydraulic Research (ASCE). The following studies are included:

Conversion of Kinetic to Potential Energy in Expanding Conduits ($74). Tests on flow through a three- to five-inch sudden expansion have been completed. A comprehensive analysis of the photographic and statistical data obtained in experiments on this project has been made. Some warping of the pyralin sections having affected the results, it is planned to make additional experiments with "Lucite" before publishing the results of the project.

Traveling Waves on Steep Slopes ($300). The extensive motion pictures of these experiments are being studied, together with the other data obtained, with a view to issuing a comprehensive report.

Phenomena of Intersecting Streams ($300). A progress report on the results obtained with intersecting closed channels was submitted to the committee. Experiments were made on both combining and diverging flow. It is planned to continue the experiments with closed channels during the coming year.

Curves in Open Channels ($300). The nature of the flow around bends has been investigated by means of a pilot tube and midget current meter as well as by photographing the movement of sawdust, confetti (for surface velocities), rice grains (bottom velocities), and drops of oil dye (interior). A mathematical analysis of the flow has been made, giving results in general agreement with the observations.

Sedimentation at the Confluence of Rivers ($300). A number of motion pictures showing the nature of the sand movement in the experimental flumes at the intersection have been made. Experiments are now being conducted with a sand having grains fairly uniform in size.

Air Resistance to Flow of Water in Open Channels ($300). Considerable study has been given to this project and a suitable flume has been designed having steep adjustable slopes.

Simultaneous Flow of Liquids and Gases in Pipes ($300). A long closed rectangular channel of transparent "Lucite" has been constructed for these experiments. Air and water will be supplied by means of a tank at the upper end and both measured by means of a tank at the lower end. Entrainment of air by water flowing down vertical drain pipes is also being studied.

Tension Tests of Large Riveted Joints (ASCE, $500). Grant was made in March 1939 to supplement funds available in the ASCE budget to make possible the publication in full in the *Proceedings* of the society a valuable article entitled "Tension Tests of Large Riveted Joints" by Raymond E. Davis, Glenn B. Woodruff, and Harmer E. Davis.

Alloys of Iron Research (AIME, $5,000). Monograph 10, "The Alloys of Iron and Nickel, Volume I—Special Purpose Alloys" was published November 1, 1938. The manuscript of monograph 11, "The Alloys of Iron and Chromium, Volume II—High-Chromium Alloys" was delivered to the publisher in August. Work has been continued on monograph 12, "The Alloys of Iron and Nickel, Volume II—Steels and Cast Iron." Recent foreign- and English-language journals were reviewed and abstracted for monographs 11 and 12. Several hundred abstracts were added to the files.

Barodynamic Researches (AIME, $2,500). The work has been continued particularly with reference to artificial support effects of longwall mining, photoelastics as applied to mine-pillar problems, a new method of measuring the *P* plus *Q* stresses in photoelastic work, a study of block caving, a study of the side pressures due to loose materials, and a study of the time effects to predict when a mine roof is likely to fail. Principles regarding artificial support in mines have been developed and artificial supports embodying these principles have been built and tested.

Effect of Temperature on the Properties of Metals (ASME, $1,000). A preprint of a report of joint research committee was submitted to the June 1939 meeting of the American Society for Testing Materials. It gave brief information concerning 11 research projects and appendices contained 3 technical papers. The work is being continued.

Critical Pressure Steam Boilers (ASME, $1,000). The studies on the viscosity of steam have been completed and a paper will be presented at the annual meeting of

ASME in December 1939. The work on the corrosion of steels at high temperature is in progress and a paper probably will be submitted during the next fiscal year.

Fluid Meters (ASME, $1,000). For several years the committee has had in progress a research investigation to determine the coefficients for flow nozzles. This has required much test work and the raising of a large fund to carry it on. The major task now is to correlate the data and arrange it for presentation. Articles on this research in the technical press have kept industry informed of its progress.

Lubrication (ASME, $1,000). The committee's work is progressing along four distinct lines: (*a*) the continuation and further development of the work on the mechanics of thick oil films; (*b*) correlation and publication of data on boundary lubrication, obtained in laboratories; (*c*) the general problem of thermodynamics of bearings; (*d*) the pressure-velocity relationships. Work on the bibliography of lubrication is progressing.

Cottonseed Processing (ASME, $500). Studies in cooker designs for continuous and automatic operation were initiated, as were studies for the purpose of improving the design of the batch type of cooker to permit economies in the manufacturing cost of the unit. Suitable automatic controls were also investigated for possible application with the batch type of cooker. To satisfy the demands of the industry, a commercial humidifier was designed, built, and placed in commercial operation for demonstration purposes. Specially designed hydraulic press plates were built to the specifications and installed during the concluding two weeks of experimental crushing operations on cottonseed only. Preliminary data indicate that the new press plate design permits a more rapid flow of oil which should permit shorter pressing cycles, thereby imparting greater pressing capacity. No perceptible improvement in total oil yield was obtained.

Rolling Steel (ASME, $800). A special tension apparatus has been designed and built, in which bars one inch in gauge length and $^3/_{16}$-inch in diameter can be pulled in tension at temperatures up to 1,200 degrees centigrade, and at high stretching velocities. Bars are heated in an induction furnace, which can be connected to an existing oscillator equipment. It is hoped that with this apparatus the yield stresses required to deform steel at temperatures from 20 to 12 degrees centigrade at a side range of velocities may be determined.

Mechanical Springs (ASME, $500). This grant has been used to assist in financing the publication of a treatise entitled "Strength of Metals with Special Reference to Spring Materials and Stress Concentration" by D. J. McAdam and R. W. Clyne.

Riveted Joints (ASME, $500 plus $399.13). These grants were made to provide for the publication of a bibliography constituting "A Critical Review of the Literature Concerning Riveted Joints." Unsuccessful attempts were made to collect enough funds to provide for 1,000 copies of a printed book. It is now proposed to print about 300 copies at the smallest practicable cost for limited distribution.

Stability of Impregnated-Paper Insulation (AIEE, $2,000 plus $267). The current year has seen the completion of a study of the influence of a variation in the density of the paper on the stability of high-voltage impregnated-paper insulation, and the completion of a similar study of the variation of the thickness of the paper of one value of density as used in practice. A number of auxiliary studies on the mechanism of breakdown in impregnated paper have been highly successful in that it became possible to interrupt the process of breakdown or failure at shorter and shorter intervals after it begins, so that much new light has been thrown on the hitherto obscure problem of the original causes of failure. These programs were planned in conferences between an advisory committee of the AIEE, a similar committee from an association of manufacturers of high-voltage cables (IPCEA), and the committee in charge of this research. The results obtained have excited great interest among the engineers of manufacturing and public-utility companies.

Welding Research Committee (AIEE and American Welding Society, $4,000 plus $5,439 reappropriated). Forty-eight reports were issued by the committee during the past year. Of these 18 related to fundamental research investigations; 11 resulted from the activities of the industrial research division; 12 were critical digests of the world's literature prepared under the auspices of the literature division; and the remainder were of a general nature. These reports covered a wide variety of subjects, including resistance welding, electrodes, stress distribution in welds subject to bending, welding arcs, spot welding low-carbon and stainless steels, crater formations in arc welding, residual stresses in pipe welding, photoelastic studies of stress distribution, miscellaneous investigations in the structural field, welds at low temperatures, control of distortion, welding of silicon bronze, weldability of medium-carbon steels, copper welding, spot, arc, and gas welding of aluminum alloys, nickel-clad steels, and effect of carbon and manganese on weldability. The literature reviews covered such subjects as molybdenum steels, copper steels, effect of oxygen, effect of aluminum on the welding of steel, internal stresses in castings, welding coated steel, effect of sulphur and phosphorus on steel, welding chromium steels, coatings and fluxes in the welding of steel, oxygen cutting of steel, effect of carbon in plain carbon steels, and the welding of copper steels.

Committee F—Fatigue Testing (Structural). The specifications for welding highway and railroad bridges prepared by the AWS in co-operation with the American Railway Engineering Association and the American Association of State Highway Officals assign certain values to welded joints subject to variable stresses. The fatigue values in these specifications are based upon European test results. It is desirable that a comprehensive set of data on unit design stresses of welds subjected to varying stresses be made available in this country on American materials and using American technique. Such data are also needed in the design of naval and other vessels, and in other structures subject to dynamic stresses. A comprehensive program is in progress. Some $25,000 has been contributed by government bureaus and industrial organizations, and other organizations have contributed materials and services. The first progress report was presented at the annual meeting of the AWS in October 1939.

Engineers' Council for Professional Development (General program $500, engineering schools $3,500). Work of the following committees is included:

Committee on Engineering Schools. The committee has continued to concentrate on its major objective, the accrediting of engineering curricula. During the year 4 new institutions, representing a total of 7 curricula, were inspected, and 74 curricula already provisionally accredited were reinspected. In addition, 9 curricula, rejected as a result of previous inspections, were reinspected. To date, 144 out of a total of 150-odd degree-granting engineering institutions have applied to the committee for inspection, and 687 curricula have been acted upon or are now under consideration. With the work of initial inspection and recommendation so nearly complete, the committee has directed its attention toward insuring the continued reliability of its list of accredited curricula. It also has devised and proposed a method of financing the continuing program of reinspections. Out-of-pocket expenses incurred in visiting institutions will be covered by an annual accrediting fee paid by institutions having curricula accredited, the fee paid by any one institution to be based on engineering enrollment and the number of curricula accredited. More than half the institutions involved already have approved the plan and only two have disapproved. In 1938 the committee secured funds from the Carnegie Foundation for the Advancement of Teaching to defray the cost of analyzing the vast amount of data collected during the course of the accrediting program. The report of this study has been completed and is now being printed.

Selection and Guidance of Engineering Students. The committee has continued to encourage the formation of guidance committees of engineers to co-operate with high-school principals in counseling with boys who are thinking of an engineering career. Numerous cities have well-functioning committees. About 7,000 copies of "Engineering: a Career—a Culture" have been distributed since October 1938, and a revision is now in progress.

Professional Recognition. The committee has reviewed the different agencies by which certificates are awarded, which are more or less generally accepted as indicating "professional recognition" and finds that these vary widely. There are: (*a*) the engineering societies, both the leading professional societies and prominent state or local societies. The national societies have different grades of membership which differ in title and in the requirements for admission; and they deal with particular fields of engineering; (*b*) the engineering schools, which grant degrees for graduate study; their character differs widely—some are broad and some are specialized, many are of recent development; no accrediting has been made and they vary in requirements as to curricula and experience; (*c*) the state registration boards which grant certificates for the legal practice of professional engineering. These are relatively new; about 90 per cent of them have been created within 20 years, and a third of them within the past 4 years. There are now 42 states having registration laws, in general similar but a number below the average standard. These boards are, in general, appointed by the state governors. Experience is an essential requirement, this to be "satisfactory to the board." Examinations are required by most of the boards. There is a National Council of State Boards of Engineering Examiners, a voluntary organization which aims to secure more effective and uniform administration of the state laws. Consistent practices by the several states in maintaining a common standard of competency is dependent upon the voluntary action of these states.

Plastic Flow of Concrete (University of California, $2,000). Work has been continued on a study of thermal stresses on slabs. The observations on the slab during the period when its temperature rose and fell, due to heat of hydration of the cement and to natural dissipation of heat, have been completed. Work is in progress on an investigation of the plastic flow of concrete in shear. A series of tests of plastic flow during the early hardening period is being made. Tests on the plastic flow of large cylinders of job concrete of several ages are under way.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and the other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Sequence Components and the Wye-Delta Transformation

To the Editor:

The problem presented by unbalanced loads or faults supplied through a wye-delta transformation has been treated by various authors (see bibliography) but the following presentation appears to the writer to possess a certain directness and generality of attack that may be of assistance to students and others.

Figure 1*a* shows a diagram of the bank connections (three single-phase transformers) with *polarity* and *terminal designation* as shown. These data, in conjunction with the *bank ratio of transformation*, are essential to the calculation of the "complex voltage and current transformation factors" that must be applied in the solution of the problem. It is assumed that the bank is supplied with a known unbalanced voltage at the supply end of the primary feeder. Transverse constants are neglected, and symmetry is assumed between source and load.

It is well known that the wye-delta transformation shifts the positive-sequence voltage and current in one direction, and the negative-sequence values an equal amount in the opposite direction. Thus, in the figure, the shift in positive-sequence voltage (as we proceed from secondary to primary circuit) is *backward* 30 degrees, while the negative sequence is shifted *forward* the same amount. In general the following complex transformation factors will apply:

$$V_{a1}=nV''_{a1}\overline{\diagdown\phi} \qquad V_{a2}=nV''_{a2}\underline{/\phi}$$

$$I_{a1}=\frac{I'_{a1}}{n}\overline{\diagdown\phi} \qquad I_{a2}=\frac{I'_{a2}}{n}\underline{/\phi}$$

where n is the "bank transformation ratio" (not winding-winding), the voltages are true line-to-neutral values, and the currents are true line values (not winding values necessarily).

Figure 1*b* shows the sequence networks for the case considered, recognizing in the separation of the secondary and primary circuits the divergent relationships which will apply to the sequence components in the two circuits; however, the circuit relations are tied together rigorously by the complex transformation factors previously referred to. No zero-sequence voltages or currents are present in the case considered, so that the corresponding network is omitted.

The following equations may then be written, wherein the primed and double-primed voltages, currents, and ohms represent true secondary values, and the unprimed quantities are true primary values. The small z's are the positive-, negative-, and zero-sequence *component* impedances derived from the unbalanced impedances making up the load. Vector voltages and currents are indicated throughout; the impedances are complex numerics.

From standard relationships:

$$V'_{a1}=I'_{a1}z'_0+I'_{a2}z'_2 \tag{1}$$

$$V'_{a2}=I'_{a1}z'_1+I'_{a2}z'_0 \tag{2}$$

Also:

$$V''_{a1}=I'_{a1}Z'_{L1}+V'_{a1}=I'_{a1}Z'_{L1}+I'_{a1}z'_0+I'_{a2}z'_2=I'_{a1}(Z'_{L1}+z'_0)+I'_{a2}z'_2 \tag{3}$$

$$V''_{a2}=I'_{a2}Z'_{L2}+V'_{a2}=I'_{a2}Z'_{L2}+I'_{a1}z'_1+I'_{a2}z'_0=I'_{a1}z'_1+I'_{a2}(Z'_{L2}+z'_0) \tag{4}$$

Equations 1 to 4 inclusive are in true secondary volts, amperes, and ohms.

Again, from fundamental theory:

$$E_{a1}=I_{a1}Z_1+V_{a1} \tag{5}$$

$$E_{a2}=I_{a2}Z_2+V_{a2} \tag{6}$$

Equations 5 and 6 are in true primary volts, amperes, and ohms. Now

$$I_{a1}=\frac{I'_{a1}}{n}\overline{\diagdown\phi} \tag{6a}$$

and

$$V_{a1}=nV''_{a1}\overline{\diagdown\phi} \tag{6b}$$

Substituting equations 6*a*, 6*b*, and 3 into 5 we have:

$$E_{a1}=\frac{I'_{a1}}{n}\overline{\diagdown\phi}\,Z_1+nV''_{a1}\overline{\diagdown\phi}=\frac{I'_{a1}}{n}\overline{\diagdown\phi}Z'_1n^2+nI'_{a1}(Z'_{L1}+z'_0)\overline{\diagdown\phi}+nI'_{a2}z'_2\overline{\diagdown\phi}$$

where Z'_1 is Z_1 in secondary equivalent value (ohms). Thus:

$$E_{a1}\underline{/\phi}/n=I'_{a1}(Z'_1+Z'_{L1}+z'_0)+I'_{a2}z'_2 \tag{7}$$

Also:

$$I_{a2}=\frac{I'_{a2}}{n}\underline{/\phi} \tag{7a}$$

and

$$V_{a2}=nV''_{a2}\underline{/\phi} \tag{7b}$$

Substituting equations 7*a*, 7*b*, and 4 into 6 we have:

$$E_{a2}=\frac{I'_{a2}}{n}\underline{/\phi}Z_2+nV''_{a2}\underline{/\phi}=\frac{I'_{a2}}{n}\underline{/\phi}Z'_2n^2+nI'_{a2}(Z'_{L2}+z'_0)\underline{/\phi}+nI'_{a1}z'_1\underline{/\phi}$$

where Z'_2 is Z_2 in secondary equivalent value (ohms). Thus:

$$E_{a2}\overline{\diagdown\phi}/n=I'_{a1}z'_1+I'_{a2}(Z'_2+Z'_{L2}+z'_0) \tag{8}$$

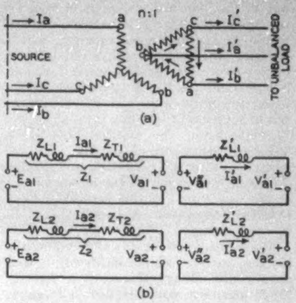


Figure 1

The left-hand members of equations 7 and 8 may be defined as the voltages impressed on the circuit in secondary equivalent values. Evidently, these equations may be solved for I'_{a1} and I'_{a2}. With these current components known, complete calculations may be readily carried out, using the various relations indicated in conjunction with well-known sequence-component synthesis. Faults, balanced load, or balanced voltage impressed at the source are merely special conditions of the general case, which is also readily extended to the case of two or more banks of transformers operated in tandem. Analogous relations apply to the delta-wye.

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Very truly yours,

WALTER A. CURRY (A'17, F'37)

(Assistant professor of electrical engineering, Columbia University, New York, N. Y.)

Why So Few Famous Engineers Today?

To the Editor:

One hundred and sixty years ago it was written:

> "It is a great and necessary proof of wisdom and sagacity to know what questions may be reasonably asked. For if a question is absurd in itself and calls for an answer where there is no answer, it does not only throw disgrace on the questioner, but often tempts an uncautious listener into absurd answers, thus presenting, as the ancients said, the spectacle of one person milking a he-goat, and of another holding the sieve." (Kant, *Critique of Pure Reason*.)

The question at the head of this letter, which serves as the text for the editorial in the October issue of ELECTRICAL ENGINEERING, seems to come within the scope of the quotation on two counts:

1. The underlying assumption cannot be admitted without proof, and no method of proof appears.

Any one of your readers can readily name several engineers, still active, whose accomplishments will measure up to those of any of the "famous" engineers in your list or in any list that can be compiled. It would be invidious to mention names, since for every one named I should probably omit two or three equally worthy of note, but I could present a formidable list of living engineers whose eminence no one would question.

Furthermore, the number of eminent living engineers cannot fairly be compared with a roster which goes back to Leonardo da Vinci, but only with the number living at any one time. If this be done I think it will be found that the implication of the question is false.

Many years ago there was a conundrum popular among school children: "Why does a dog always sneeze three times?" Much ingenuity was exercised in attempts to explain this peculiar phenomenon. The correct answer was: "He doesn't."

2. What do you mean by a "famous" engineer? Is it the same as "notorious?" Do you mean one whose name appears frequently in the daily press and is bandied about among those who have no conception of engineering? Or do you mean one whose work has constituted a substantial advance in engineering art and science, although, in all probability, the crowd never heard of him? If the former, the fewer "famous" engineers, the better.

Showmanship (the word is a shock to the sensibilities of a professional man, but it appears twice in your editorial) may contribute to financial success, but no serious-minded engineer was ever consciously a showman.

The late Thomas B. ("Czar") Reed was once asked his definition of a statesman. He replied: "A statesman is a politician who is dead." Like most epigrams, this is only a half truth. Nearly all the "famous" engineers in your list are dead; some of them are not otherwise distinguished.

Most engineers spend their lives doing routine and conventional things in accordance with "good practice." Only at long intervals appear a few men who are intellectually far above the general level, who do not feel bound to copy the work of their predecessors, and who do not think that good practice is determined, like the choice of a Congressman, by the vote of mediocrity. Such men are rarely heard of by the public. They are eminent but not "famous."

One man builds a mile of road and attracts no attention. Another builds a thousand miles and is touted as a great engineer, although the only difference between them is that the second man has spent a thousand times as much money as the first. Such is fame!

Few great men have been recognized as such by their contemporaries. It is only after they have ceased to run that the crowd catches up with them. Schopenhauer did most of his work as a young man but received no recognition until shortly before his death. "Time has brought its roses at last," he said, "but see," touching his silvered hair, "they are white."

One must choose whether he will have the high opinion of his own kind, which comes only if it is merited, or the manufactured and meaningless press publicity which caters to a low form of personal vanity.

The whole matter has been tersely put in one of Mr. Arthur Guiterman's verses:

"Some men are famed for genius, knowledge, power,
  And service to humanity; and some
Are talked about, like Pisa's leaning tower,
  Because they're out of plumb."

Which do you want? Enduring fame after you are gone, or vulgar notoriety while you live? You may never have either but you can't have both.

Only a decadent civilization rates a man's achievements by the roar of the crowd.

Very truly yours,

CHARLES W. COMSTOCK (A'03, M'38)

(Consulting engineer, Jackson Heights, N. Y.)

Magnesium-Copper Sulphide Rectifier Battery Charger

To the Editor:

In the September 1939 issue of ELECTRICAL ENGINEERING I noted with interest F. J. Bartholemew's comments on C. A. Kotterman's paper dealing with magnesium-copper sulphide rectifiers. It seems to me that the magnesium-copper sulphide rectifier, due to its low efficiency and short life, is the one that should *not* be considered seriously as a heavy-duty industrial type of rectifier. Both the selenium and copper oxide rectifiers appear to show over-all efficiencies almost twice as high as that of the copper sulphide rectifier. Copper oxide rectifiers have proved their long life and there are thousands of these units in operation all over the world. Some of these installations have exceeded 12 years of continuous operation.

The selenium-iron rectifier is relatively new and has been used mostly in Germany, possibly due to the scarcity of copper. Life tests have not progressed as far as those on the copper oxide rectifier. Up to 1936 the selenium cells had a relatively short life, and it is only since 1936 that some improvements have been made, and all indications point toward a longer life. However, it can be stated with a fair degree of accuracy that up to the present time there is no dry rectifier on the market that has proved to have a long life comparable to the copper oxide rectifier, since tests on the selenium rectifiers which show merit have only been running for three years.

Very truly yours,

E. A. HARTY (A'22, M'36)

(Street lighting engineering department, General Electric Company, West Lynn, Mass.)

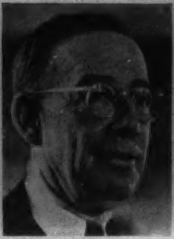
Personal Items

F. R. Maxwell, Jr. (M'30) professor of electrical engineering, University of Alabama, Tuscaloosa, has been elected AIEE vice-president for District 4, by action of the board of directors following the resignation of E. E. George. He was born in Tuscaloosa, June 15, 1889, and received the degrees of bachelor of science in mechanical engineering (1911), mechanical engineer (1912), and electrical engineer (1923) from the University of Alabama. In 1912 he was employed by the Tuscaloosa Ice and Light Company, working on various aspects of plant operation. When the company became the Tuscaloosa Railway and Utilities Company, in 1915, he was made commercial manager, and after two years (1917–19) in the United States Naval Reserve, he returned in 1919 to be assistant general manager. He became instructor in electrical engineering and physics at the University of Alabama in 1920, becoming assistant professor the following year, associate professor in 1923, and full professor in 1934. He is counselor of the AIEE Student Branch at the University of Alabama, a member of the AIEE membership committee, and was vice-chairman of District 4. He has also been chairman of the Alabama Section. He is a member of the Society for the Promotion of Engineering Education and of Tau Beta Pi.

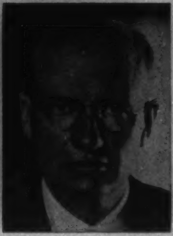
F. R. MAXWELL, JR.

H. A. Lardner (A'94, F'13) vice-president, J. G. White Engineering Corporation, New York, N. Y., has been elected president of United Engineering Trustees, Inc., joint agency of the national engineering societies. He was born October 1, 1871, at Oconomowoc, Wis., and received the degree of bachelor of science in electrical engineering in 1893 and that of electrical engineer in 1895 from the University of Wisconsin. He was engaged on railway construction work for J. G. White and Company, at Baltimore, Md., in 1894–95. During the next two years he was an instructor in electrical engineering at Pennsylvania State College, State College, Pa., returning to J. G. White and Company in 1897 to work in Buffalo and New York, N. Y. He became assistant electrical engineer at the New York office in 1900, then chief electrical engineer, and general manager of the engineering department. In 1909 he was made general manager of the San Francisco office of the company, where he remained until 1915. He was made a vice-president and director of

H. A. LARDNER


J. P. HOGAN

W. F. DAVIDSON


O. E. BUCKLEY

L. M. GOLDSMITH

the J. G. White Engineering Corporation in 1913. Since 1915 he has been in New York. He is a member of The American Society of Mechanical Engineers, and past-president of the New York Electrical Society, and has been a member of the board and vice-president of UET, Inc.

O. E. Buckley (M'19, F'29) executive vice-president, Bell Telephone Laboratories, Inc., New York, N. Y., has been elected vice-president of the Engineering Foundation, joint research agency of the national engineering societies. Born at Sloan, Iowa, August 8, 1887, Doctor Buckley received the degree of bachelor of science from Grinnell College, 1909, and that of doctor of philosophy from Cornell University, 1914, and the honorary degree of doctor of philosophy from Grinnell in 1936. He was an instructor in physics first at Grinnell and then at Cornell, and in 1914 joined the technical staff of Western Electric Company, from which Bell Telephone Laboratories was later derived. He has continued with that organization ever since, except during 1917–18, when he was in charge of the laboratory of the United States Army Signal Corps in Paris, France. He was made assistant director of research at Bell Laboratories in 1927, director of research in 1933, and executive vice-president in 1937. He has been active on AIEE technical committees and is a member of the Franklin Institute, American Physical Society, and American Association for the Advancement of Science.

J. P. Hogan (M'31) member of firm of Parsons, Klapp, Brinckerhoff, and Douglas, consulting engineers, New York, N. Y., has been officially nominated for president of the American Society of Civil Engineers for 1940. He was born June 12, 1891, at Chicago, Ill., and attended Harvard University, receiving the degrees of bachelor of arts (1903) and bachelor of science (1904). After about two years as assistant engineer for the New York, N. Y., Rapid Transit Commission, he was employed by the New York, N. Y., Board of Water Supply in 1906 as assistant engineer on the construction of the Catskill Aqueduct. In 1911 he became division engineer, continuing in that position until 1917. He served in France until 1919, attaining the rank of lieutenant-colonel on the United States Army General Staff, and on his return was acting deputy chief engineer for the New York Board of Water Supply. In 1920 he went with the firm of Parsons, Klapp, Brinckerhoff, and Douglas, directing the New York water power investigation 1920–23. He has been a member of the firm since 1926, specializing in power development. He was chief engineer and director of construction of the New York World's Fair 1936–39, continuing as vice-president and chief engineer consultant for the Fair Corporation. He has served as a director and vice-president of the ASCE and is a member of The American Society of Mechanical Engineers.

W. F. Davidson (A'14, F'26) director of research, Consolidated Edison Company of New York, Inc., New York, N. Y., and recently appointed chairman of the AIEE committee on research, has been appointed by the National Research Council to the chairmanship of its conference on electrical insulation. A biographical sketch of Mr. Davidson appeared in the October issue, page 443.

L. M. Goldsmith (M'26) chief engineer, Atlantic Refining Company, Philadelphia, Pa., has been awarded the Melville Medal of The American Society of Mechanical Engineers for his paper "High-Pressure High-Temperature Turbine-Electric Steamship J. W. Van Dyke." The medal is awarded annually for the best original paper on a mechanical-engineering subject presented to the Society. Mr. Goldsmith was born July 1, 1893, at Pottsville, Pa., and graduated in electrical engineering from Drexel Institute of Technology in 1914. During the next two years he was employed by the Perpetual Fuse Company and the United Gas Improvement Company, both of Philadelphia, and by the City of Philadelphia Department of Public Works. He went with the Atlantic Refining Company in 1916 as a mechanical draftsman, and held successively the positions of experimental engineer, engineer of tests, technical assistant to the president, and consulting engineer. In 1934 he was made manager of the general engineering and construction department, and in 1937 chief engineer. He is a vice-president and director of the Atlantic Pipe Line Company, and a director of the Atlantic Oil Shipping Company, subsidiaries of the Atlantic Refining Company. He is a member of The American Society of Mechanical Engineers, American Society of Naval Engineers, Society of Automotive Engineers, American Welding Society, and other organizations, and has made various contributions to technical literature.

M. B. Long (A'19) has been appointed assistant to the executive vice-president, Bell Telephone Laboratories, Inc., New York, N. Y., to co-ordinate the work of the various organizations and individuals concerned with building and equipping the Laboratories' new building at Murray Hill, N. J. Since graduating with the degree of bachelor of science from the University of Nebraska in 1917, Mr. Long has been assistant physicist, Bureau of Standards, Washington, D. C., 1917–19; research engineer, Western Electric Company, New York, N. Y., 1919–25; educational director, Bell Telephone Laboratories, 1925–30. Since 1930 he has been assistant director of publications. He had charge of the Bell System exhibits at the New York World's Fair, the Chicago Exposition, of 1933, and other recent expositions.

H. W. Button (A'19) has been appointed vice-president in charge of operations of the Laclede Power and Light Company, St. Louis, Mo. He was graduated in electrical engineering from Worcester Polytechnic Institute in 1912, and spent the following three years with the Westinghouse Electric and Manufacturing Company. He became assistant engineer for the Connecticut Company, New Haven, in 1915, and was later with Stone and Webster, Boston, Mass., the American Railways Company, Philadelphia, Pa., and the Eastern New Jersey Power Company, Allenhurst. He has been associated with the Laclede company for some years.

C. J. Holslag (M'19) president, general manager, and chief engineer, Electric Arc Cutting and Welding Company, Newark, N. J., has been awarded the Samuel Wylie Miller Memorial Medal of the American Welding Society. He was selected as the person who, in the judgment of the board of awards, was "most deserving for conspicuous contributions to the advancement of welding or cutting of metals." He was born at Addison, N. Y., December 13, 1885, and received the degree of electrical engineer from Columbia University in 1908. After graduation he entered the electrical-engineering department of the New York Central Railroad, later becoming resident engineer at Amsterdam, N. Y. He continued with the railroad until 1918, but was

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C. J. HOLSLAG

also associated with organizations engaged in the manufacture of electrodes from 1915. In 1918 he took part in the organization of the Electric Arc Cutting and Welding Company, of which he became chief engineer, and later president and general manager. He holds numerous patents, is the author of the Arc Welding Handbook and other contributions to technical literature, and is a member of the American Welding Society and the American Electrochemical Society.

Y. H. Ku (A'27, M'34) was appointed vice-minister of education by the Chinese National Government in January 1938, and since that time has worked with the minister of education on China's wartime educational program. Doctor Ku, who is dean of engineering, National Tsing Hua University, Peiping, China, was born December 24, 1902, at Wusih, Kiangsu Province, China. He is a graduate of Tsing Hua College, and holds the degrees of bachelor of science in electrical engineering (1925), master of science (1926), and doctor of science (1928) from Massachusetts Institute of Technology. During 1928 he was employed for short periods at the East Springfield, Mass., works of the Westinghouse Electric and Manufacturing Company, and by the General Electric Company, Schenectady, N. Y. He returned to China in 1929 to become head of the electrical-engineering department, National Chekiang University, Hangchow, and in 1931 became dean of the engineering college, National Central University, Nanking. He went to Tsing Hua University in 1932 to establish the engineering school. He is a director of the Chinese Institute of Engineers, one of the founders of the Chinese Institute of Electrical Engineers, and author of technical papers in Chinese and in English.

J. A. French (M'22) has been appointed chief engineer of the Guardian Manufacturing and Supply Corporation, New York, N. Y. He was born August 2, 1892 at Waltham, Mass., and received the degree of bachelor of science in electrical engineering from Tufts College in 1914. Following graduation he was employed as a special apprentice in the electric locomotive shop of the New York, New Haven, and Hartford Railroad. In 1916 he entered the construction department of the power Construction Company, Worcester, Mass., and the next year was employed by the H. M. Hope Engineering Company as resident electrical engineer on construction for the Eastern Connecticut Power Company. He went with the latter company in 1919 as construction superintendent, becoming electrical engineer in 1921. When the company became the eastern division of the Connecticut Power and Light Company, in 1928, he became research engineer for the eastern division, continuing in that position until 1938. He was electrical engineer in the consulting division of Day and Zimmermann, Philadelphia, Pa., until his present appointment. He is a past-chairman of the AIEE Connecticut Section.

E. F. Heath (A'37) has been appointed senior valuation engineer, New York State Public Service Commission, New York, N. Y. He had been associated with the Brooklyn Edison Company, Brooklyn, N. Y., since 1919, having been inspector of apparatus, assistant on the survey which preceded the system's change from direct to alternating current, and later engaged in cost accounting, estimating, and engineering analyses. Since 1934 he had been engaged on valuation work for the establishment of continuing property records for the system. He was graduated in electrical engineering from New York University in 1937.

C. L. Sampson (A'25, M'39) has been appointed plant engineer, Minnesota area, Northwestern Bell Telephone Company, Minneapolis, Minn. Mr. Sampson, who holds the degrees of bachelor of science, master of science, and electrical engineer, from the University of Minnesota, had been engineer of transmission, protection, and plant extension for the Iowa area of the company since 1928, and prior to that time was an instructor in electrical engineering at the University of Minnesota, Minneapolis.

R. W. Griffiths (A'39) is now production planner, production engineering department, Boeing Aircraft Company, Seattle, Wash. He was formerly a student engineer with L. R. Teeple Company, Portland, Ore., and engaged on a power and transmission line survey for the Bonneville Dam project.

S. E. Schultz (A'25) formerly electrical engineer, Port of New York Authority, New York, N. Y., is now consulting electrical engineer, Bonneville Dam project, Portland, Ore.

J. R. Perkins, Jr. (A'36) has been appointed assistant professor of engineering physics, Grove City College, Grove City, Pa. He received the degree of electrical engineer at Princeton University in 1935, and last year held a teaching fellowship in physics at Massachusetts Institute of Technology, Cambridge.

W. S. Gifford (A'16) president, American Telephone and Telegraph Company, New York, N. Y., is a member of the committee of industrialists appointed by the National Association of Manufacturers to select outstanding inventors to be honored as "Modern Pioneers."

W. M. Bauer (A'29, M'36) has been appointed lecturer in electrical engineering, University of Minnesota Institute of Technology, Minneapolis. He was formerly instructor in electrical engineering at Northwestern University, Evanston, Ill., and since 1937 has been a graduate student and teaching assistant at Harvard University, Cambridge, Mass.

David Sarnoff (M'23) president, Radio Corporation of America, New York, N. Y., is a member of the committee of industrialists appointed by the National Association of Manufacturers to select outstanding inventors to be honored as "Modern Pioneers."

J. A. Mathews (A'37) formerly junior engineer with the United States Bureau of Mines, Central Experiment Station, Pittsburgh, Pa., is now a junior patent engineer, United States Patent Office, Washington, D. C.

A. B. Hallman (A'38) formerly in charge of aircraft electrical maintenance at the Newark station of Eastern Air Lines, Inc., is now an electrical technician for the company at Miami, Fla.

T. C. Smith (A'37) formerly range engineer, Edison General Electric Appliance Company, Chicago, Ill., is now engineer in charge of electric-range section, appliance division, Stewart Warner Corporation, Indianapolis, Ind.

F. J. McDonald (A'38) is now an electrical engineer in the office of the Quartermaster General, construction division, War Department, Washington, D. C. He was formerly in the electrical design department, E. I. du Pont de Nemours and Company, Wilmington, Del.

O. T. Mundt (A'37) formerly transformer tester for Westinghouse Electric and Manufacturing Company, Sharon, Pa., is now an engineer at the East Pittsburgh works of the company.

W. G. Whitsitt (A'35) formerly sales engineer, technical department, Leeds and Northrup, Philadelphia, Pa., is now design engineer, for the Breeko Corporation, Nashville, Tenn.

M. F. Davis (A'37) formerly in the United States Engineer's office, Huntington, W. Va., is now a designer for the National Advisory Committee for Aeronautics, Langley Field, Va.

C. C. Diemond (A'37) formerly junior engineer, United States Bureau of Reclamation, Ephrata, Wash., is now employed in the same capacity on the Bonneville Dam project, Portland, Ore.

C. R. Vail (A'38) has been appointed instructor in electrical engineering at Duke University, Durham, N. C. He was formerly employed by the General Electric Company and was operating engineer for the company's high-voltage demonstration at the New York World's Fair.

J. T. Holmes (M'24) formerly president, Mitchell-Vance Company, New York, N. Y., is again associated with the Frink Corporation, Long Island City, N. Y., where he will continue to work with special lighting. He had formerly been chief engineer of that company for many years.

D. F. Smith (A'31, M'35) formerly chief engineer, State of Oregon, Pacific Telephone and Telegraph Company, Portland Ore., has been transferred by the company to the position of chief engineer, Northern California and Nevada, with headquarters at San Francisco, Calif.

S. E. Warner (A'31) formerly chief engineer, radio station WBRY, Waterbury, Conn., has been appointed supervisor of the Connecticut State Police radio system. Before going to WBRY he was instructor in electrical engineering at Rensselaer Polytechnic Institute, Troy, N. Y.

K. L. Howe (A'28, F'36) has been transferred by Westinghouse Electric and Manufacturing Company from the position of district engineer, Seattle, Wash., to that of engineer, San Francisco, Calif. He has been secretary of the AIEE Seattle Section.

H. C. Wolfe (A'28) formerly rural electrification representative, Monongahela West Penn Public Service Company, Fairmont, W. Va., is now manager of the O and A Electric Co-operative, Newaygo, Mich., which serves ten counties in that area.

A. J. Fischer (A'36) is now metallurgist with the Frith-Sterling Steel Company, McKeesport, Pa. He was formerly with American Cutting Alloys, Lewiston, Maine, and the Metal Powders Processing Company, Inc., Long Island City, N. Y.

M. B. Marshall, Jr. (A'37) formerly student engineer, General Electric Company, Schenectady, N. Y., is now an electrical engineering assistant, New York City Board of Transportation, power division, New York, N. Y.

S. M. Wilson (A'27, M'34) has been appointed assistant engineer of manufacture, Western Electric Company, New York, N. Y. He was formerly manager of the company's central office division at Kearny, N. J.

Leif Holst (A'23, M'30) formerly designer, American Gas and Electric Service Corporation, New York, N. Y., is now an associated electrical engineer with the ordnance bureau of the United States Navy Department, Washington, D. C.

S. H. Hanville, Jr. (A'39) formerly assistant manager, Ashland Lumber and Supply Company, Newcomerstown, Ohio, is now employed by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

L. B. Bryan (A'35) formerly steam engine and generator operator, Joseph E. Seagram and Sons, Inc., Lawrenceburg, Ind., is now a junior agricultural engineer for the soil conservation service, United States Department of Agriculture, Ottawa, Kans.

S. E. Clements (A'39) has been appointed instructor in electrical engineering at the University of Kansas, Lawrence. He formerly held a similar position at Iowa State College, Ames.

L. D. Harris (A'38) is now instructor in electrical engineering, University of Utah, Salt Lake City. He received the degree of master of science in electrical engineering from Purdue University in 1939.

R. B. Capron (A'30, M'35) has been made distribution engineer for the Central New York Power Corporation, with headquarters at Watertown, N. Y. He was formerly district engineer, Potsdam, N. Y.

G. C. Morris (A'35) formerly junior electrical engineer, Sunbeam Electric Manufacturing Company, Evansville, Ind., has been employed as an engineer by the A. G. Redmond Company, Owosso, Mich.

A. M. Dayton (A'39) formerly assistant field engineer, E. B. Badger and Sons Construction Company, Toledo, Ohio, is now associated with the Howell Electric Motor Company, Howell, Mich.

J. J. Thomason (A'19, M'25) has been transferred to Memphis, Tenn., by the Westinghouse Electric and Manufacturing Company. He was formerly manager of central station sales, St. Louis, Mo.

J. S. Lieb (A'35) formerly a student engineer at Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has been transferred to the New York office of the company as representative.

C. R. Hine (A'37) formerly special apprentice, Pennsylvania Railroad Company, Philadelphia, Pa., is now instructor in industrial arts, East Side High School, Newark, N. J.

A. P.-T. Sah (A'35, M'36) president of Amoy University, is now located at Changting, Fukien Province, China, where the university has been removed because of war conditions.

G. A. Palka (A'39) formerly junior engineer, Federal Emergency Administration of Public Works, Chicago, Ill., is now employed as a designing engineer by the Standard Transformer Company, Warren, Ohio.

A. S. Anderson (A'26, M'38) formerly assistant superintendent of distribution, New Orleans Public Service, Inc., New Orleans, La., is now associated with Ebasco Services, Inc., New York, N. Y.

D. R. Frantz (A'39) formerly junior engineer, Washington Institute of Technology, College Park, Md., is now employed by the Bell Telephone Laboratories, Inc., New York, N. Y.

M. M. Belknap (A'31) formerly electrical inspector, Iowa Electric Light and Power Company, Perry, has been transferred to Cedar Rapids as chief electrician, Boone district.

R. S. Taylor (A'36) formerly division engineer, Oklahoma Gas and Electric Company, Muskogee, is now with the district engineering department of the company at Oklahoma City.

C. R. Dixon (A'35) formerly assistant plant engineer, Mount Hope Finishing Company, North Dighton, Mass., is now electrical engineer, The Aluminum Company of America, New Kensington, Pa.

R. A. Krasovec (A'31) formerly a switchboard operator for the Tennessee Valley Authority at Norris, Tenn., is now electrician, International Smelting and Refining Company, Perth Amboy, N. J.

H. F. Danneman, Jr. (A'32) formerly industrial engineer, Tide Water Associated Oil Company, New York, N. Y., has been transferred to Boston, Mass., as regional engineer for the company.

S. V. Swanson (A'30) formerly chief engineer, Refrigerator Appliances, Inc., Chicago, Ill., is now associated with the engineering department of the Young Radiator Company, Racine, Wis.

C. R. Delagrange (A'30) formerly foreman, Firestone Rubber and Latex Products Company, Fall River, Mass., is now a textile engineer, Celanese Corporation of America, Narrows, Va.

R. B. Harder (A'38) formerly instructor in electrical engineering, Iowa State College, Ames, is now employed as electrical test engineer by the Electromotive Corporation, LaGrange, Ill.

W. W. Winter (A'38) formerly a student apprentice with Allis-Chalmers Manufacturing Company, West Allis, Wis., has been appointed sales engineer for the company's Chicago, Ill., office.

R. E. Lyle (A'32) formerly electrical engineer, Department of Utilities, City of Tacoma, Wash., is now junior engineer, Bonneville Dam project, Portland, Ore.

G. W. Bills (A'38) former graduate teaching assistant at the University of Washington, Seattle, is now a junior electrical engineer, Bonneville Dam project, Portland, Ore.

T. B. Jones, Jr. (A'35) formerly with the Linde Air Products Company, Pittsburgh, Pa., is now with Commonwealth and Southern Corporation, Jackson, Mich.

E. C. Hillman (A'37) has been appointed a junior engineer, for the ordnance bureau, United States Navy Department, Washington, D. C.

C. J. Eiwen (A'39) is now a junior welding engineer for the ordnance bureau, United States Navy Department, Washington, D. C.

O. L. Worden (A'35) formerly valuation engineer, New York State Electric and Gas Company, Ithaca, N. Y., is now employed by Crouse-Hinds Company, Syracuse, N. Y.

B. H. Ormson (A'22) formerly chief electrician, Ruby Gulch Mining Company, Zortman, Mont., is now employed by the Montana Power Company, Cut Bank.

D. H. Shick (A'39) is now a graduate teaching assistant at the University of Missouri, Columbia, while working toward a master's degree.

H. W. von Dohlen, Jr. (A'36) formerly radio operator, Station WRUF, Gainesville, Fla., is now associated with Eastern Air Lines, Inc., Miami, Fla.

E. R. Groo (A'35) formerly supervisor, Aerovox Corporation, Brooklyn, N. Y., is now cash control manager, Consolidated Molded Products Company, Scranton, Pa.

M. P. Naab (A'32) formerly general construction supervisor, Wisconsin Telephone Company, Appleton, has been appointed district plant manager at Appleton.

W. L. Cassell (A'25) formerly associate professor of electrical engineering, University of Colorado, Boulder, now holds the same position at Iowa State College, Ames.

U. N. Halliday (A'28) sales engineer, Pacific Electric Manufacturing Company, has been transferred from San Francisco, Calif., to Denver, Colo.

R. P. Posey (A'39) is now junior electrical engineer, Rudolph Wurlitzer Manufacturing Company, North Tonawanda, N. Y.

V. E. Gardner (A'39) is now an instructor in electrical engineering, University of North Dakota, Grand Forks.

Jules Cohen (A'39) is now employed as a junior electrical engineer on the Bonneville Dam project, Portland, Ore.

S. R. Hribar (A'38) has been employed as an electrical draftsman by Commonwealth and Southern Corporation, Jackson, Mich.

H. C. Green (A'39) is now employed in construction engineering for the Carolina Power and Light Company, Southern Pines, N. C.

Obituary

Edwin Dow Wood (A'21, M'26) general superintendent, Louisville Gas and Electric Company, Louisville, Ky. and vice-president 1937–39 of AIEE District 4, died November 9, 1939. He was born April 17, 1878, at Montevideo, Uruguay, and attended high school at Callao, Peru. He received the degree of bachelor of science from DePauw University in 1903, and during 1903 and 1904 was employed by the Union Traction Company of Indiana, the Pope-Waverly Electric Company, Indianapolis, and the General Electric Company, Schenectady, N. Y. In 1904 he went to Lima, Peru, in the employ of the Empresa Electrica Santa Rosa, which later became the Empresas Electricas Associadas. He became assistant chief engineer and was acting chief engineer when he resigned in 1909 to become construction department foreman for General Electric at Schenectady. In the following year he was transferred to the engineering department of the Cincinnati district. He became electrical operating engineer for the Louisville Gas and Electric Company in 1915, was made electrical engineer in 1926, and general superintendent in 1932. He was elected a director of the company in 1936. He was a past-chairman of the AIEE Louisville Section, and completed his term as vice-president of District 4 August 1, 1939. He was also a past-president of the Engineers and Architects Club of Louisville.

Paul N. Nunn (A'95, M'96) president, Telluride Power Company, Salt Lake City, Utah, died October 27, 1939 at San Diego, Calif. He was born at Medina, Ohio, July 31 1860, educated for the teaching profession, and engaged in teaching and business until 1890. He then went to Telluride, Colo., becoming consulting engineer for the San Miguel Consolidated Gold Mining and Gold King Mining companies. In connection with the development of electric power for mines, he was associated with the design and installation of one of the first commercial high-voltage a-c transmission systems to be put into successful operation. The Telluride Power Company, which grew out of that enterprise, built the first electric power plant in Utah in 1897, and for a time was said to be the most powerful high-voltage system in the world. It extended through Colorado, Montana, Utah, and Idaho. Mr. Nunn was chief engineer for the company 1890 to 1910, and during 1903–10 was also chief engineer for the Ontario Power Company, Niagara Falls. In 1917 he became president and director of the present Telluride Company, continuing to hold that position until his death, although he had been retired from active professional work for some time. He was a member of the American Society of Civil Engineers and The American Society of Mechanical Engineers.

William Kemp Vanderpoel (A'08, M'21) vice-president, The Okonite Company, and the Okonite Callender Cable Company, New York, N. Y., died October 21, 1939 at South Orange, N. J. He was born at New York, May 29, 1880, and educated there. His engineering career began as cadet engineer on trans-Atlantic liners in 1897, after which he was engaged in shop electrical work; on drafting for the New York and New Jersey Telephone Company; in mining in South America; with the Red Telephonica Company, then operating in Havana, Cuba; as a bank cashier in New York; and as assistant purchasing agent for the Florida East Coast Railroad and Hotel companies. In 1908 he became associated with the Public Service Electric Company, Newark, N. J., as division superintendent, becoming general superintendent in 1916. He was appointed vice-president and executive engineer of The Okonite Company in 1926. He was a manager of the AIEE 1923–27, and had been active on technical committees. He was also active in the National Electric Light Association, and was the author of many technical papers.

Gerald John Wagner (M'20) president, G. J. Wagner and Company, consulting engineers, Grand Rapids, Mich., died September 2, 1939. Born in Grand Rapids May 28, 1886, he received the degree of bachelor of science in electrical engineering from the University of Michigan in 1910. He was employed by the Metropolitan Street Railway Company, New York, N. Y., and the Grand Rapids-Muskegon Power Company, before becoming an electrical engineer for the Michigan Railway Engineering Company, Kalamazoo, in 1912. In that capacity and as general superintendent he was engaged in construction of electric third-rail lines until 1916, when he became superintendent of construction for the Michigan Railway Company, Jackson. He was city engineer for the City of Grand Rapids 1918–19, becoming director of public service for the City in 1920. In 1922 he established his own private consulting firm, acting as consultant for the City of Grand Rapids and other cities, Michigan Public Utilities Commission and other state commissions, and for various utility and industrial companies. He was a member of The American Society of Mechanical Engineers, past-president, Michigan Engineering Society, and member of local engineering organizations.

William R. Garton (A'05) retired, Pelham, N. Y., died September 15, 1939. He was born July 20, 1868, and studied electrical engineering at Coe College. In 1889 he began electrical railway construction work at Des Moines, Iowa, under the Thomson Houston Electric Company, later becoming associated with the Mississippi Valley Construction Company in charge of work at Keokuk, Iowa. In about 1892 he formed a company for the manufacture of the Garton lightning arrester, which he had invented and patented. In 1894 he became manager of the railway department of the Central Electric Company, Chicago, Ill., and in 1898 organized the W. R. Garton Company, acting as president and general manager. About ten years later he became general manager of the manufacturing department, Lord Electric Company, New York, N. Y., and later vice-president. He was afterward sales engineer for various companies, including the Edison Storage Battery Company. He was long associated with the Walker Vehicle Company, New York, as sales engineer, assistant to the eastern district manager, and later New York district sales manager. During the early 1930's he was vice-president of the Sarvas Electric Company, New York.

Walter Robinson McRae (M'17) superintendent of rolling stock and shops, Toronto Transportation Commission, Toronto, Ontario, Canada, died during the summer of 1939, according to information recently received at Institute headquarters. He was born at Bolsover, Ont., October 21, 1874, and educated in Toronto. From 1887 to 1891 he was employed successively for short periods by various electric companies in Toronto and St. Catherine's, and during 1891–92 was with the electrical department of Bennett and Wright Company, Toronto, installing equipment in the Toronto School of Science. In 1892 he was engaged to supervise installation of car equipment in the electrification of the Toronto Railway Company, and continued in the employ of that and associated companies for many years, on railway electrification, installation, and operation of power plant equipment. In 1904 he became general foreman of shops of the Toronto Railway Company, and in 1907 master mechanic in charge of rolling stock and shops. About 15 years later he went with the Toronto Transportation Commission.

Johnston Livingston (A'98) head of the engineering and construction firm of his name, New York, N. Y., died October 10, 1939. He was born in New York, December 19, 1876, and was graduated from Columbia University in 1898 with the degree of electrical engineer. The following year he was associated in the formation of the United Engineering and Contracting Company, New York, of which he was vice-president, and in 1900 he formed the firm of Johnston Livingston, Jr., and Company, electrical engineers and contractors. That organization was incorporated in 1909 as J. Livingston and Company, with Mr. Livingston as president, and engaged in a wide variety of electrical and power plant engineering and construction. About 14 years ago he left that company to form the construction firm of Johnston Livingston which he headed until his death.

David Humphrey Johnston, Jr. (M'28) assistant electrical engineer, Consolidated Gas, Electric Light, and Power Company, Baltimore, Md., died September 12, 1939, in Chicago, Ill. He was born at Baltimore, November 24, 1891, and received the degree of bachelor of science in electrical engineering from Johns Hopkins University in 1916. He was a second lieutenant in the United States Army Engineering Corps during 1917–19, and assistant to the director of terminal facilities for the American Expeditionary Forces. In 1919 he was employed as inspector by the Consolidated Gas, Electric Light, and Power Company, Baltimore. He became superintendent of electrical service in 1922, with responsibility for all electrical construction, and had recently become assistant electrical engineer.

Louis Homer Bayha (A'33) industrial service man, central manufacturing district, Leeds and Northrup Company, Los Angeles, Calif., died September 17, 1939, at San Gabriel, Calif. He was born September 14, 1909, in Los Angeles, and received the degree of bachelor of science in electrical engineering in 1932 from the University of Southern California. During his senior year he acted as laboratory assistant in electrical engineering. After graduation he was employed as junior electrician by the Shell Company of California, Wilmington, for about two years, before going to Leeds and Northrup as industrial engineer. He was a member of Eta Kappa Nu.

Lloyd Gilroy Hagenbuch, Jr. (A'34) junior engineer, Ford Instrument Company, Inc., Long Island City, N. Y., died October 1, 1939. He was born June 4, 1912, at New York, N. Y., and was graduated from Rensselaer Polytechnic Institute in 1933 with the degree of electrical engineer. He was employed for some months in the engineering division of the Federal Emergency Administration of Public Works, Washington, D. C., and by Gibbs and Hill, consulting engineers, on the electrification of the Wilmington-Washington route of the Pennsylvania Railroad, before going with the Ford Instrument Company. He was a member of Sigma Xi.

John Tak Sang Fung (A'35) administration engineer, Kwangtung Wireless Administration, Canton, China, died some months ago, according to information recently received at Institute headquarters. He was born at Kohala, Hawaii, March 16, 1909, and received the degree of bachelor of science in electrical engineering at Heald Engineering College in 1933. He designed and constructed a low-power broadcast transmitter for the Chinese Government during 1933–34, and in 1934 was appointed by the Government to the position he held at the time of his death. He was a member of the Institute of Radio Engineers.

Membership

Recommended for Transfer

The board of examiners, at its meeting on November 16, 1939, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Hazeltine, H. L., engineer of insulation, The Sterling Varnish Company, Haysville, Pa.
Homan, J. G., private research, writing, 8700 Ventnor Avenue, Atlantic City, N. J.
Kalb, W. C., advertising department, National Carbon Company, Cleveland, Ohio.
Miner, D. F., professor, Carnegie Institute of Technology, Pittsburgh, Pa.
Wildes, K. L., associate professor of electrical engineering, Massachusetts Institute of Technology, Cambridge.

5 to Grade of Fellow

To Grade of Member

Beavers, M. F., development engineer, General Electric Company, Pittsfield, Mass.
Farry, O. T., transformer engineer, Wagner Electric Corporation, St. Louis, Mo.
Gross, I. W., electrical research engineer, American Gas and Electric Service Corporation, New York, N. Y.
McKibben, W. E., research engineer, General Electric Company, Schenectady, N. Y.
Mittag, A. H., electrical engineer, General Electric Company, Schenectady, N. Y.
Morey, C. V., assistant meter engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.
Sasscer, W. H., engineer in electrical & mechanical department, Pennsylvania Coal Company, Scranton.
Vaughan, C. F., assistant head of estimate section, General Electric Company, Pittsfield, Mass.

8 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before December 31, 1939, or February 29, 1940, if the applicant resides outside of the United States or Canada:

United States and Canada

1. NORTH EASTERN

Connors, J. J., Irvington Varnish and Insulator Company, Irvington, N. J.
Hershey, J. D., General Electric Company, Buffalo, N. Y.
Lazur, E., Babcock Printing Press Corporation, New London, Conn.
Martin, H. W., Allis-Chalmers Manufacturing Company, Boston, Mass.
McLachlan, W. J., General Electric Company, Schenectady, N. Y.
Mortimer, A. J., Federal Shipbuilding and Dry Dock Company, Kearny, N. J.
Murphy, H. E. (Member), Stone and Webster Engineering Corporation, Boston, Mass.
Ripley, E. B., Jr., Connecticut Light and Power Company, Devon, Conn.
Schifino, A. G., Rochester Radio Supply Company, Rochester, N. Y.
Shott, H. S., General Electric Company, Schenectady, N. Y.
Sisterhenm, M. L. (Member), Danbury and Bethel Gas and Electric Light Company, Danbury, Conn.
Stubbs, S. R., Allis Chalmers Manufacturing Company, Boston, Mass.

2. MIDDLE EASTERN

Bond, G. W., Ohio Public Service Company, Massillon.
Bourne, R. F. (Member), Federal Power Commission, Washington, D. C.
Carlson, E. G., Bell Telephone Company of Pennsylvania, Philadelphia.
Cunningham, W. A., 831 Linden Street, Allentown, Pa.
Dimity, C. D., Copper Wire Engineering Association, Washington, D. C.
Eldridge, G. C., Jr., Bell Telephone Company of Pennsylvania, Philadelphia.
Filler, C. F., Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md.
Hyer, R. J. (Member), Copper Wire Engineering Association, Washington, D. C.
Kelly, W. J., Bell Telephone Company of Pennsylvania, Philadelphia.
Keneipp, H. E., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Kutcher, W. J., Electric Controller and Manufacturing Company, Cleveland, Ohio.
Lory, M. R., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Moss, C. R., Hickok Electrical Instrument Company, Cleveland, Ohio.
Prasse, H. E. (Member), Atlantic Refining Company, Philadelphia, Pa.
Sherburne, R. G., Bliss Electrical School, Takoma Park, D. C.
Smith, R. C., Philadelphia Electric Company, Philadelphia, Pa.
Standring, J. M., Jr., Bell Telephone Company of Pennsylvania, Philadelphia.
Steiner, L. S., Timken Roller Bearing Company, Canton, Ohio.
Steinert, W. E., Bell Telephone Company of Pennsylvania, Philadelphia.
Stover, H. N. (Member), Philco Radio and Television Corporation, Philadelphia, Pa.

3. NEW YORK CITY

Gunnison, G. S., Consolidated Car Heating Company, Inc., New York, N. Y.
Levine, S., 1136 Metcalf Avenue, Bronx, New York, N. Y.
Li, T. C., 1017 John Jay Hall, Columbia University, New York, N. Y.
Loomis, S. D. (Member), Federal Advisers, Inc., New York, N. Y.
Mapes, C. M. (Member), American Telephone and Telegraph Company, New York, N. Y.
Palmer, W., Sperry Gyroscope Company, Brooklyn, N. Y.
Quinn, J. L., Jr., National Broadcasting Company, New York, N. Y.
Sordon, E. P., Consolidated Edison Company, New York, N. Y.
Sowards, C. C., Copperweld Steel Company, New York, N. Y.
Stainken, H. A., Otis Elevator Company, New York, N. Y.

4. SOUTHERN

Allebaugh, R. O., Virginia Public Service Company, Harrisonburg.
Bodemuller, H. R. (Member), Louisiana Public Utilities Company, Inc., Lafayette.
Harrington, J. L., Southwestern Gas and Electric Company, Shreveport, La.
Murphree, D. D., Southwestern Gas and Electric Company, Shreveport, La.
Tarwater, C. E., Knoxville Electric Power and Water Board, Knoxville, Tenn.
Underwood, J. L., Jr., 302 Walton Building, Atlanta, Ga.
Vannort, B. O. (Member), 1207 Commercial Bank Building, Charlotte, N. C.

5. Great Lakes

Boyajian, J. A., J. P. Seeburg Corporation, Chicago, Ill.
Carter, B. H., Sanitary District of Chicago, Chicago, Illinois.
Cox, I. W. (Member), Cutler Hammer, Inc., Milwaukee, Wis.
Cross, R. D., Detroit Institute of Technology, Detroit, Mich.
DeFrees, J. T., Hubbard and Company, Cicero, Ill.
Ferguson, P. M., Jr., American Automatic Electric Sales Company, Alexandria, Minn.
Gadler, S., Rural Electrification, St. Paul, Minn.
Lockwood, R. R., Brown, Jackson, Boettcher, and Dienner, Chicago, Ill.
Marple, C. N., Iowa Public Service Company, Sioux City.
Northcott, J. A., Jr. (Member), University of Notre Dame, Notre Dame, Ind.
Stander, L. F. (Member), University of Notre Dame, Notre Dame, Ind.
Stiles, K. P. (Member), American Telephone and Telegraph Company, Springfield, Ill.
Witty, B. G., Allis Chalmers Manufacturing Company, Milwaukee, Wis.

7. South West

Duncan, C. C., American Telephone and Telegraph Company, Dallas, Tex.
Hubbell, M. F (Member), Union Electric Company of Missouri, St. Louis.
Laisure, T. H., Kansas Gas and Electric Company, Wichita.
Lienesch, J. P., Southwestern Bell Telephone Company, St. Louis, Mo.
Martin, D. D., Southwestern Light and Power Company, Lawton, Okla.
Mathers, R. S., Oklahoma Gas and Electric Company, Oklahoma City.
McClain, O. E., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Milligan, B., Oklahoma Gas and Electric Company, Oklahoma City.
Peacock, V., Dallas Power and Light Company, Dallas, Tex.
Wallace, P. G., Texas Power and Light Company, Dallas.
Ward, D. S., United Light and Power Service Company, Kansas City, Mo.

8. Pacific

Hewlett, W. R., Hewlett Packard Company, Palo Alto, Calif.
Pettengill, C. L., Public Works Administration, San Francisco, Calif.
Ralston, E L., Jr., Westinghouse Electric and Manufacturing Company, San Francisco, Calif.
von Seeburg, A. L., Pacific Electric Manufacturing Corporation, San Francisco, Calif.

9. North West

Eastman, A. V. (Member), University of Washington, Seattle.
Gogins, J. F., General Electric Company, Spokane, Wash.
Munakata, Y., Puget Sound Power and Light Company, Seattle, Wash.
Ross, J. S. (Member), Bonneville Project, Seattle, Wash.

10. Canada

Brown, J. A., Jr., Bell Telephone Company of Canada, Toronto, Ont.
Hardie, R. C., Canadian General Electric, Ltd., Vancouver, B. C.

Total, United States and Canada, 83

Elsewhere

Malkani, H. U., Indian Cable Company, Ltd., Bombay, India.
Roy, J. K. (Member), British Insulated Cables, Ltd., Calcutta, India.

Total elsewhere, 2

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Doherty, Joseph F., 901 Hill St., Wilkinsburg, Pa.
Evans, David T., Box 194, Anyox, B. C., Can.
Hollifield, Ray, 5118 Milam St., Dallas, Texas.
Keiser, M., 1841 Broadway, New York, N. Y.
Lovett, Morris, Diehl Manufacturing Company, Elizabethport, N. J.
O'Fiel, J. C. Dudley, Jr., 1214 Chartres St., Houston, Texas.
Pyne, Arnold N., 627 Third St., Niagara Falls, N. Y.
Sanchez, Hector M., 12 De Diegos Ave., Santurce, Puerto Rico.
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RADIO INTERFERENCE SUPPRESSION. By G. W. Ingram. London, Electrical Review, 1939. 154 pages, illustrated, 8 by 5 inches, cloth, 5s. Written to provide a link between the activities of the power-plant engineer and the radio and communication systems engineer. The various causes of interference with radio reception from electrical equipment are classified in such a way, both in the text and the appendices, that the type and probable cause of interference can be readily recognized, and the method of remedy easily selected.

INDUSTRIAL SOLVENTS. By I. Mellan. New York, Reinhold Publishing Corporation, 1939. 480 pages, illustrated, 9 by 6 inches, cloth, $11.00. The first six chapters discuss the theory of solution and the general properties of solvents. The following chapters discuss the use of solvents in industries and provide specific information about available solvents, arranged under the following classes: hydrocarbons, halogenated hydrocarbons, alcohols, aldehydes, acids, ketones, ethers, esters, and plasticizers. Many diagrams and tables.

BIG BUSINESS AND RADIO. By G. L. Archer. New York, American Historical Company, 1939. 503 pages, illustrated, 10 by 6 inches, cloth, $4.00. A companion volume to the author's "History of Radio to 1926," the present book overlaps the former as a result of the inclusion of a large amount of new material concerning the struggle in the early 1920's among the groups interested in the field. Continuing from there the story covers subsequent developments and disturbances in connection with talking pictures, television, facsimile, and the general expansion of radio broadcasting. Free use is made of direct quotation, and the part played by various personalities has received full consideration.

APPLIED ECONOMICS FOR ENGINEERS. By B. Lester. New York, John Wiley and Sons, 1939. 464 pages, diagrams, etc., 9 by 6 inches, cloth, $4.00. Provides an introduction to the practical aspects of economics, based upon the conditions and problems encountered in engineering practice. Stressing the importance of habitual reference to current technical literature the author presents practical information on industrial relations and organization, standards, statistical and accounting methods, development and production problems, costs, markets, distribution, and sales.

COMPANY PLANS FOR EMPLOYEE PROMOTIONS. By H. Baker. Princeton, N. J., Industrial Relations Section of Princeton University, 1939. 48 pages, charts, 10 by 7 inches, paper, 75¢. This pamphlet presents a brief analysis of the promotion programs of representative industrial companies. General procedures in promotional programs, training for promotion, publicity on programs and opportunities and the effect of promotional plans are discussed.

ELECTRICAL ENGINEERING. By B. E. Kimberly. Scranton, Pa., International Textbook Company, 1939. 324 pages, illustrated, 9 by 5 inches, flexible, $2.75. Written specifically for the use of engineering students not majoring in electrical engineering, this textbook presents a comprehensive survey of fundamental theories, practices, and machinery. The information presented has been chosen to assist the engineer in the intelligent selection of equipment and in dealing with electrical problems.

ELECTRICITY AND MAGNETISM. By J. B. Whitehead. New York and London, McGraw-Hill Book Company, 1939. 221 pages, diagrams, etc., $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $3.00. A compact presentation of the physical and mathematical theories, intended for fourth-year undergraduate students of physics and electrical engineering. The text follows the approximate chronological order of the classical development of electrical and magnetic science, and aims to meet the needs of those who must acquire the essentials of the theory in a relatively short time.

ELEKTRISCHE HÖCHSTSPANNUNGEN. (Technische Physik in Einzeldarstellungen, number 1). By A. Bouwers; edited by W. Meissner and G. Holst. Berlin, Julius Springer, 1939. 333 pages illustrated, $9\frac{1}{2}$ by 6 inches, cloth, 31.20 rm., bound; 29.40 rm., paper. A convenient summary of present-day developments in the production and use of high voltages (of the order of several hundred thousand volts) is supplied by this monograph. The production of such voltages is described and the resulting electrical fields discussed. Chapters are devoted to insulators, to the elements of plants, and the measurement of high voltages. Finally, applications in power transmission, materials testing, radioactivity, etc., are reviewed. Bibliography of over 300 articles.

HEAT POWER. By E. B. Norris and E. Therkelsen. Second edition. New York and London, McGraw-Hill Book Company, 1939. 432 pages, illustrated, 9 by 6 inches, cloth, $4.00. The major topies of the internal-combustion engine, steam engines, steam turbines, and boiler furnaces are presented in a simple manner, including theory, analysis of heat-cycles and performance, accessories and auxiliaries. This revised edition includes a chapter on refrigeration. Many numerical examples and problems help the student in his practical application of the information. The work varies the usual arrangement by commencing with the internal-combustion engine.

IONS, ELECTRONS, AND IONIZING RADIATIONS. By J. A. Crowther. Seventh edition. New York, Longmans, Green and Company; London, Edward Arnold and Company, 1939. 348 pages, illustrated, 9 by 6 inches, cloth, $4.00. The recent developments in the field of atomic physics are presented in this textbook, for students who have covered the elementary courses. The mathematical treatment has been simpiified in order to facilitate a better general understanding of the principles involved. Ionic charges, photo-electricity, atomic structure, and the various kinds of rays and radiations are discussed. Each chapter has a brief bibliography.

NOTIONS D'ÉCLAIRAGISME. By A. Salomon. Paris, Dunod, 1939. 189 pages, illustrated, 10 by 7 inches, paper, 58 frs.; bound 78 frs. The physical and physiological factors important in satisfactory lighting installations, the production of light, lighting equipment, and the proper illumination of residences and public buildings are covered in this textbook, which is intended to give architects, artists, and decorators a knowledge of the possibilities of modern technique.

PHYSICS. By E. Hausmann and E. P. Slack. Second edition. New York, D. Van Nostrand Company, 1939. 756 pages, illustrated, 9 by 6 inches, cloth, $4.00. Aims to present the essentials of physics to college students majoring in science or engineering. It attempts to give a gradual, logical approach to the subject, and to develop and illustrate clearly the fundamental concepts. The new edition has been revised, rearranged, in the light of teaching experience, and provided with many additional problems.

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Transactions

Papers and Discussions Comprising Pages 611–74 of the 1939 Volume

Economical Loading of High-Voltage Cables Installed in Underground Subway Systems

E. R. THOMAS
MEMBER AIEE

AN underground high-voltage cable system is made up of two major components: the cable with its joints and accessories and the underground duct and manhole structure. The question of what size of conductor should be chosen for a particular transmission feeder or as a general standard for distribution feeders has confronted every planning group. The voltage for the system is frequently limited to one or to relatively few different values already existing as a system standard, deviations from which would result in increased cost to obtain terminal facilities. Frequently some underground facilities already exist and when only a few additional feeders are being considered it might seem logical to make use of them. A study of the annual charges may show, however, in some cases, that it will be more economical to build additional new underground facilities rather than further to congest already existing structures.

Table I. Cable Technical Data

Kilovolts	Number of Conductors	Size (Thousands of Circular Mils)	Insulation (Mils)	Maximum Copper Temperature (Deg C)	Dielectric Loss (Watts per Foot)	Thermal Constants (Deg C per Watt per Foot) H$_1$	H$_2$	H$_3$
13.6	3	350	156 × 78	76.0	0.7	1.044	1.74 to 2.00	0.75
13.6	3	800	203	82.0	0.8	0.50	1.28 to 1.58	0.75
13.6	1	2500	203	82.0	0.3	0.732	1.55 to 1.84	0.75
27.0	3	350	297	74.4	1.3	0.89	1.51 to 1.67	0.75
27.0	3	500	297	74.4	1.3	0.792	1.36 to 1.63	0.75
27.0	1	1500	297	74.4	0.4	1.260	1.81 to 2.05	0.75
45.0	3	500	225	75.0	0.4	0.49	1.25 to 1.86	0.75
132.0	1	600	560	70.0	1.2	2.02	1.70 to 1.92	0.75

Since some of these questions arose in connection with the planning of tie feeders and network distribution feeders in New York City the cables in the voltage classes which were standard on that system were investigated.

Procedure

The ratings of cables installed in ducts[1] for a given load-cycle and ambient temperature will vary with the number of cables installed in the duct bank and with the size of the duct bank. A typical set of curves for one size of cable is shown in figure 1. It will be readily recognized that for any duct bank the load per cable which may be carried will become a decreasing function as more cables are installed in the bank. This causes the cost per unit of load for cables alone to increase as more cables are added due to the decrease in their rating. At the same time the proportional cost per cable for the duct bank is decreasing due to greater occupancy. The most economical combination will be determined by the ratio of costs between these two component

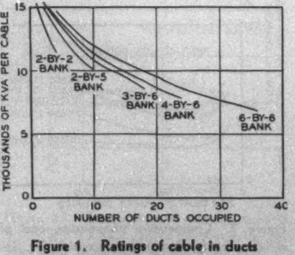

Figure 1. Ratings of cable in ducts

Three conductors, 800,000 circular mils, 13.6 kv

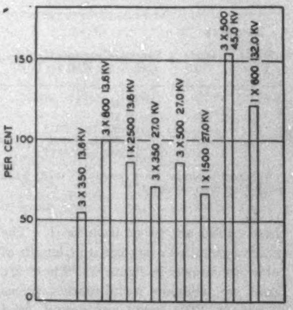

Figure 2. Relative installed cost of cable per cable foot

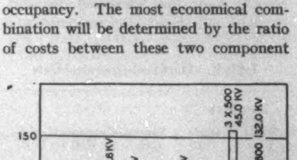

Figure 3. Relative cost of subway per duct foot

Ordinate scale same as figure 2

Paper number 39-69, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted November 25, 1938; made available for preprinting December 30, 1938.

E. R. THOMAS is division engineer of the cable division, Consolidated Edison Company of New York, Inc., New York.

The author greatefully acknowledges the help furnished by the various members of the electrical-engineering department in the preparation of this paper. He is particularly indebted to J. M. Comly in the supervision of the assembly of the data and to J. P. Neubauer and J. W. McCloskey for making the detailed calculations and numerous curves.

[1] For all numbered references, see list at end of paper.

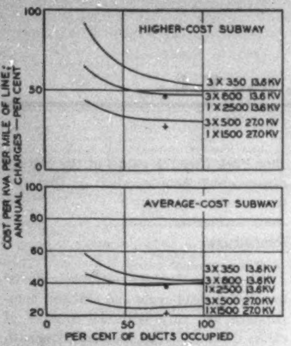

Figure 4. Comparative transmission cost of different cables installed in two-wide by two-high duct bank

parts and the respective changes in cost with increment number of cables.

The sizes of cables which have been selected in this study are typical of those found in practice and a number of them represent the largest size for that type and voltage which are suitable for installation in ducts four inches in diameter. Physical and electrical characteristics of these cables are given in table I. The relative installed costs per unit length of cable are shown in figure 2. These are based on common metal-market prices of copper $12^{5}/_{8}$ cents per pound, lead 4 cents per pound.

Table II. Duct Bank Technical Data

Duct Bank		
Ducts Wide	Ducts High	Thermal Constants $H_4 + H_5$ (Deg C per Watt per Foot)
2	2	1.500
2	5	0.857
3	6	0.667 to 0.702*
4	6	0.600 to 0.653*
6	6	0.500 to 0.571*

* Weighted average duct constant used when inner ducts were occupied.

Duct-bank and manhole costs vary over a considerable range due to the character of the soil affecting excavation and to congestion with other subsurface structures. Two unit costs for these were used in this study, one a higher-cost subway system where excavations were difficult due to soil conditions and congestions of subsurface structures, the other an average-cost subway system where excavation conditions were normal. The relative values of these are shown in figure 3.

The annual carrying charges have been calculated on the basis of 14 per cent of the installed cable cost and 12 per cent of the subway cost. These values assume an average life of 25 years for the cable and 35 years for the subway system and include interest, insurance, taxes, depreciation, operation, and maintenance. The evaluation of losses was not included since the trend changes due to cost of wasted energy are small compared to the effect of losses in limiting cable ratings.

The ratings of cables used in this study have been calculated for normal allowable copper temperatures, soil ambient of 15 degrees centigrade, cable and duct thermal constants as given in tables I and II, 40 per cent loss factor, and 85 per cent attainment factor. The loss factor is the ratio of average to peak loss in the duct bank. The attainment factor is used because the rise in temperature of the copper above the idle duct may be less when the peak load occurs periodically instead of continuously. The ratio of this actual rise to the ultimate for a continuous load is called the attainment factor. These values of loss factor and attainment factor were selected as being representative of the usual loading of duct banks and cables encountered in an underground distribution system. All

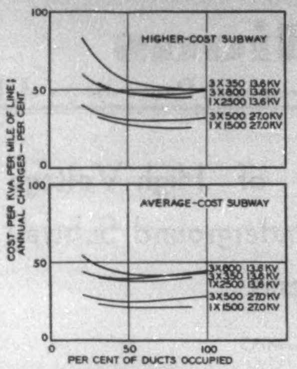

Figure 5. Comparative transmission cost of different cables installed in two-wide by five-high duct bank

Ordinate scale same as figure 4

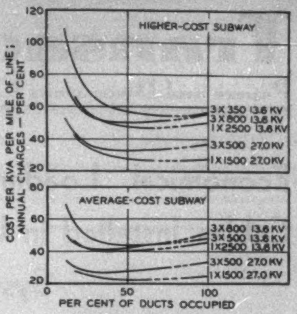

Figure 6. Comparative transmission cost of different cables installed in three-wide by six-high duct bank

Ordinate scale same as figure 4

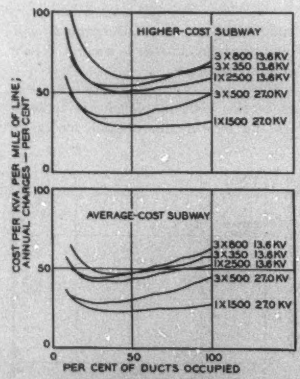

Figure 7. Comparative transmission cost of different cables installed in six-wide by six-high duct bank

Ordinate scale same as figure 4

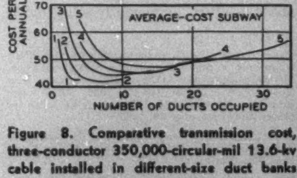

Figure 8. Comparative transmission cost, three-conductor 350,000-circular-mil 13.6-kv cable installed in different-size duct banks

Ordinate scale same as figure 4
Curve 1—Two-by-two bank
Curve 2—Two-by-five bank
Curve 3—Three-by-six bank
Curve 4—Four-by-six bank
Curve 5—Six-by-six bank

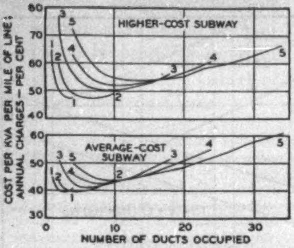

Figure 9. Comparative transmission cost, three-conductor 800,000-circular-mil 13.6-kv cable installed in different-size duct banks

Ordinate scale same as figure 4

For curve designations, see subcaption of figure 8

of the ratings assume three-phase 60-cycle operation. There may be special conditions of operation where a higher loss factor may be encountered. Since the loss factor of all the cables in a bank principally affects the temperature rise of the bank, these special conditions may indicate a somewhat lower rate of occupancy of the bank than with the load factor studied.

Results of Calculations

The annual charges for several types and voltage ratings of cable installed in common-size duct banks are shown in figures 4, 5, 6, and 7, showing relative values both for the higher subway costs and for average subway costs. These data show in general that the largest-size cable for a given voltage class which it is practical to install in a duct results in the most economical high-voltage transmission. Large single conductor cables are somewhat more economical than three-conductor cable but no account has been taken of the greater voltage regulation which obtains with single-conductor cable and which frequently may make it unsuitable for parallel operation with three-conductor cable.

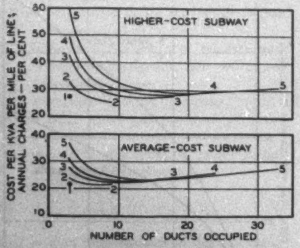

Figure 12. Comparative transmission cost, single-conductor 1,500,000-circular-mil 27-kv cable installed in different-size duct banks

Ordinate scale same as figure 4

For curve designations, see subcaption of figure 8

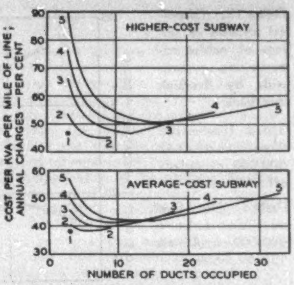

Figure 10. Comparative transmission cost. single-conductor 2,500,000-circular-mil 13.6-kv cable installed in different-size duct banks

Ordinate scale same as figure 4

For curve designations, see subcaption of figure 8

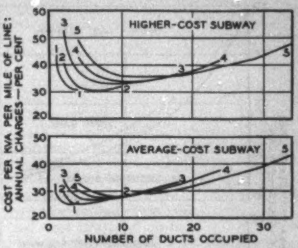

Figure 11. Comparative transmission cost, three-conductor 500,000-circular-mil 27-kv cable installed in different-size duct banks

Ordinate scale same as figure 4

For curve designations, see subcaption of figure 8

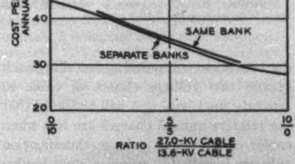

Figure 13. Comparison of transmission cost, 27-kv and 13.6-kv cables co-occupying and separately occupying two-wide by five-high duct bank

Ordinate scale same as figure 4

Table III. Effect of Load Division Between Cables in a Two-by-Five Duct Bank Containing Five Three-Conductor 500,000-Circular-Mil 27-Kv Cables and Five Three-Conductor 800,000-Circular-Mil 13.6-Kv Cables

Load (Kilovolt-Amperes)			Copper Temperature (Deg C)	
27-Kv Cables	13.6-Kv Cables	Total	27-Kv Cables	13.6-Kv Cables
90,000	0	90,000	74.4	
74,000	47,000	121,000	74.4	72.2
72,000	50,000	122,000	74.4	75.8
70,000	52,500	122,500	74.4	79.0
68,000	55,000	123,000*	74.4	82.0
65,000	55,500	120,500	72.9	82.0
60,000	56,500	116,500	68.9	82.0
55,000	57,500	112,500	65.2	82.0
0	63,000	63,000		82.0

* Maximum kilovolt-amperes is obtained when all cables are at their normal copper temperature.

When an underground high-voltage cable system is made up of one standard size of cable it becomes of interest to know when it is more economical to build new underground facilities to take care of additional cables as compared to installing them in existing facilities. The relative annual charges for several different-size duct banks are shown in figures 8, 9, 10, 11, and 12. As an illustration, it will be noted in figure 9 that if six three-conductor 800,000-circular-mil 13.6-kv cables are already installed in a two-by-five duct bank of average-cost subway and there is need for adding two, three, or four additional cables that it is more economical to build a new two-by-two duct bank to take care of these additional cables. However, if the duct bank were of higher-cost subway it would be more economical to continue to utilize the existing facilities in the two-by-five duct bank for all except the addition of four cables. It will be noted from the various data for duct banks in these figures that two-wide bank construction results in lower over-all annual charges on underground high-voltage cable systems than any of the wider bank widths. This is a somewhat fortunate condition as racking facilities in manholes are greatly improved

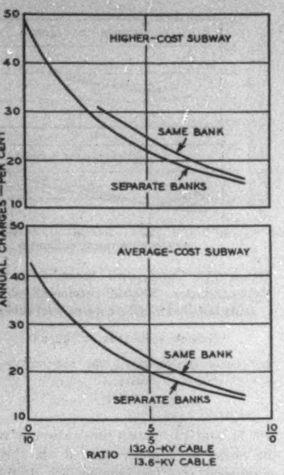

Figure 14. Comparison of transmission cost, 132-kv and 13.6-kv cables co-occupying and separately occupying two-wide by five-high duct bank

Ordinate scale same as figure 4

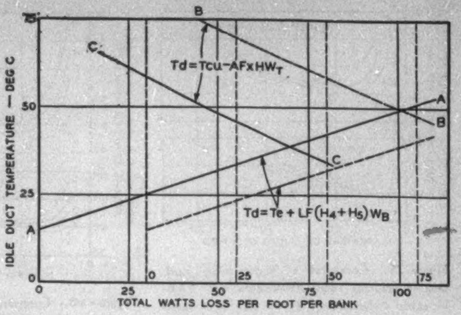

Figure 15. Graphical solution of ratings of cables co-occupying a two-wide by five-high duct bank

Solid line—Five three-conductor 500,000-circular-mil 27-kv cables

Dashed line—Five three-conductor 800,000-circular-mil 13.6-kv cables

when there is no crossing of cables over duct positions as frequently occurs when duct-bank widths of greater than two are used.

Usually more than one high-voltage class of cable exists on a system and it has been common practice to install cables operating on these different voltages in the same underground duct facilities. These cables have different maximum allowable copper temperatures and different thermal properties. Different voltage classes of cable which are not widely different in their thermal properties and which are installed in two-wide duct banks usually will transmit the maximum kilovolt-amperes through the bank when the load is so proportioned between the two classes of cable that they both reach their allowable copper temperature at the same time. A typical set of data is shown in table III for variously apportioning load on five three-conductor 800,000-circular-mil 13.6-kv cables and five three-conductor 500,000-circular-mil 27-kv cables installed in a two-wide by five-high duct bank. Similar data are shown in table IV for six single-conductor 600,000-circular-mil 132-kv cables and four three-conductor 800,000-circular-mil 13.6-kv cables. This illustration, which deals with cables of widely different voltage classification, shows the marked reduction in capacity which obtains due to occupancy of the same subway system. In order to study the limiting condition when two different voltage classes of cable are installed in a common duct bank we have found that the graphic solution as described in appendix I is very helpful.

Under a given set of conditions the maximum load which may be transmitted on both types of cable through the duct bank may not necessarily be the most economical manner in which to transmit the load. If we consider a system made up of a sufficiently large number of cables of two voltage classes and compare the relative annual charges of installing those cables as a mixed system in common duct banks as compared to installing each of the two voltage classes of cable in separate duct banks, it will be found that the relative annual charges are less when cables of the same voltage classification only are installed in common duct banks. The comparison between three-conductor 800,000-circular-mil 13.6-kv cables and three-conductor 500,000-circular-mil 27-kv cables is shown in figure 13 and a similar comparison between three-conductor 800,000-circular-mil 13.6-kv cables and single-conductor 600,000-circular-mil 132-kv cables is shown in figure 14. However, when the increment number of cables to be added in an existing system of other-voltage cable is small, the most economical arrangement will have to be studied as a specific case.

Table IV. Effect of Load Division Between Cables in a Two-by-Five Bank Containing Six Single-Conductor 600,000-Circular-Mil 132-Kv Cables and Four Three-Conductor 800,000-Circular-Mil 13.6-Kv Cables

Load (Kilovolt-Amperes)			Copper Temperature (Deg C)	
132-Kv Cables	13.6-Kv Cables	Total	132-Kv Cables	13.6-Kv Cables
279,000	0	279,000*	70.0	
222,000	43,000	265,000	70.0	72.0
217,000	45,000	262,000	70.0	77.6
211,000	48,000	259,000	70.0	82.0
192,000	48,300	240,300	66.0	82.0
168,000	49,000	217,000	62.0	82.0

* Maximum kilovolt-amperes is obtained when there is no load on the 13.6-kv cables.

Conclusion

1. Increased operating economies will obtain by properly co-ordinating the selection and loading of cables in specific duct banks.

2. The use of duct banks having more than two-wide arrangements in general are not economical.

3. The construction of new underground facilities frequently may result in a more economical system as a cable system is being expanded, than would an increase in congestion of existing facilities.

4. In general, it is not economical to install cables of widely different voltage classification in a common duct bank.

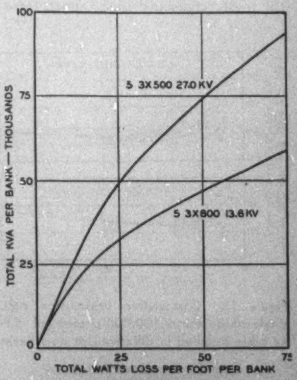

Figure 16. Heat loss in two-wide by five-high duct bank

Appendix I. Graphical Method of Determining the Effects of Load Division on Kilovolt-Amperes for a Duct Bank Containing Cables of Two Voltage Classes

The effects of load division on kilovolt-amperes for a duct bank containing cables of two voltage classes may be determined graphically. This method requires curves of idle duct temperature versus watts loss, the curves for different cables being plotted on separate sheets, and curves of kilovolt-amperes versus watts for each cable.

By superimposing one set of curves on another, the watts loss for each cable at rated copper temperature, or the watts loss on one cable if the loss on the other is known, may be determined. The watts may be converted to kilovolt-amperes by a kilovolt-amperes-versus-watts curve. It is possible also to determine the copper temperature of the cables that are operating below their rated copper temperature.

Two idle-duct temperature curves are needed for each cable, one calculated by subtracting the thermal drop from copper to idle duct from the rated copper temperature (equation 1) and one calculated by adding the thermal drop from idle duct to base earth to the earth ambient (equation 2).

$$T_d = T_{cu} - AF \times (H_1 + H_2 + H_3)W_t \quad (1)$$

T_d = idle duct temperature in degrees centigrade

T_{cu} = copper temperature in degrees centigrade

H_1 = thermal constant for insulation (Simmons)

$= \dfrac{0.00522\ RG_1}{N}$

H_2 = thermal constant, sheath to duct wall

$= \dfrac{4.9}{D(1 + 0.013W_t)}$

H_3 = thermal constant, duct wall to idle duct, 0.75 (Kirke). H_1, H_2, and H_3 are in degrees centigrade per watt per duct foot

AF = attainment factor for rise of copper above idle duct

R = thermal resistivity of insulation in degrees centigrade per watt per centimeter cube

G_1 = geometric factor (Simmons)

W_t = total watts loss per duct per duct foot

D = outside diameter of cable—inches

N = number of conductors

$$T_d = T_e + LF \times (H_4 + H_5)\ W_t \quad (2)$$

T_d = duct temperature in degrees centigrade

LF = loss factor for duct bank

$H_4 + H_5$ = thermal constant for duct bank in degrees centigrade per watt per duct foot (Kirke)

W_t = total watts loss per duct foot for the duct bank

T_e = earth temperature in degrees centigrade

In equation 1 values for the total watts loss per foot of cable are assumed, and the idle duct temperature is calculated. If there are five cables of one type in the bank, this idle-duct temperature is plotted against five times the assumed watts per cable. Values of total watts per foot per bank are assumed for equation 2.

The application of the graphical method is shown in the following example. Assuming a two-by-five bank containing five three-conductor 500,000-circular-mil 27-kv cables having a total loss of 30 watts per foot and five three-conductor 800,000-circular-mil 13.6-kv cables, the problem is to find the kilovolt-amperes which can be transmitted through the bank and the copper temperature of the 27-kv cables if the 13.6-kv cables are at rated copper temperature.

Idle-duct temperature curves are drawn for each cable and the 13.6-kv curves are placed on the 27-kv curves so that the zero-watt 13.6-kv ordinate coincides with the 30-watt 27-kv ordinate. This is shown in figure 15 where the curves for each cable are drawn on one sheet to simplify the explanation in preference to using separate sheets. The 13.6-kv cables will be at rated copper temperature where the cable and bank duct temperature curves *AA* and *BB* intersect. The watts loss for the five 13.6-kv cables is found by projecting this point to the 13.6-kv watt scale to be 71 watts. Using the kilovolt-amperes-watts curves (figure 16) for the five 27-kv and five 13.6-kv cables the kilovolt-amperes per each set of cables is found and added to get the bank kilovolt-amperes. By repeating this process for various assumed watts loss on each set of cables the correct load division for maximum kilovolt-amperes may be found.

The kilovolt-amperes-watts curves are calculated using resistance and dielectric loss values at rated copper temperature. This will introduce some error when one type of cable is operating below the rated copper temperature.

The copper temperature of the 27-kv cables in the example given is found in the following manner: The idle-duct temperature of the bank is indicated by the intersection of *AA* and *BB* to be 49.5 degrees centigrade. However, at 30 watts per foot on the five 27-kv cables the thermal drop from rated copper to idle duct indicates a required duct temperature of 58.5 degrees centigrade as shown by the intersection of *CC* and the zero-watt 13.6-kv ordinate. The difference between the actual duct temperature and this required duct temperature, 9.0 degrees centigrade, subtracted from the 27-kv rated copper temperature, 74.4 degrees centigrade, gives a copper temperature of 65.4 degrees centigrade for the 27-kv cables.

Bibliography

1. THE CALCULATION OF CABLE TEMPERATURES IN SUBWAY DUCTS, **Wallace B. Kirke.** AIEE JOURNAL, October 1930.

2. REDUCTION OF SHEATH LOSSES IN SINGLE-CONDUCTOR CABLES, **Searing and Kirke.** *Electrical World*, October 6, 1928.

3. CALCULATION OF THE ELECTRICAL PROBLEMS OF UNDERGROUND CABLES, **Simmons.** *The Electric Journal*, May to November 1932.

Discussion

L. I. Komives (nonmember; The Detroit Edison Company, Detroit, Mich.): The data presented in table IV, concerning the effect of load division between cables of widely different voltage ranges, certainly merits considerable interest. It is, of course, understood that the cables described were compared on the basis of normal temperature limits. However, as oil-filled cables can be operated at higher temperatures than solid-type cables with the same factor of safety, this table should be used only when all other factors are taken into consideration.

J. M. Comly (Consolidated Edison Company of New York, Inc., New York): In Mr. Thomas' paper, figures 8, 9, 10, 11, and 12 show curves of relative annual cost per kilovolt-ampere for various combinations of cables and ducts. It may be of interest to mention an investigation of the effect on these curves of changes in copper temperature and loss factor.

The normal kilovolt-amperes used in calculating cost per kilovolt-ampere might be reduced in practice by the necessity of carrying contingency loads on some of the cables without exceeding their normal allowable copper temperature. Thus a reduction in copper temperature for normal operation would be necessary. Similarly, loads of different types would result in different daily loss factors. Obviously if changes in these constants materially affect the relative costs for different cable and duct combinations, the curves presented in the paper will not show the relative economy of these different combinations except for very special cases.

A study of the effect of changing copper temperature for the special case of three-conductor 800,000-circular-mil 13.6-kv cable indicates that changes in copper temperature from the normal allowable value of 82 degrees centigrade to 50 degrees centigrade and even to 30 degrees centigrade make no appreciable change either in the point of lowest cost nor in the relative costs in different-size duct banks.

Mr. Thomas' data are based on an assumed daily loss factor of 40 per cent. It seems unlikely that the load of large-capacity distribution feeders would vary its character more than would be indicated by a variation in loss factor from 30 per cent to 50 per cent. In this range, the changes in location of the point of minimum cost are negligible for three-conductor 800,000-circular-mil 13.6-kv cable operating in a two-by-five duct bank. If the range is from 20 per cent to 100 per cent, the point of minimum cost in the curves of cost per kilovolt-ampere versus number of ducts loaded may vary as much as two ducts.

In conclusion, it appears from a study of the effects of changes in these two essential constants that the relative costs shown by Mr. Thomas' curves would be reasonably accurate for all practical operating conditions within the range of subway and cable costs shown.

W. F. Davidson (Consolidated Edison Company of New York, Inc., New York): In figure 1 of his paper, Mr. Thomas has used a figure of 1.3 watts per foot for the dielectric loss on 27-kv three-conductor cables. This is probably a representative value but it is by no means a maximum. In the course of some laboratory studies a few years ago, it was found that some cables, when subjected to overload-cycle aging tests, experienced a very large increase in dielectric loss. This suggested the desirability of examining samples removed from service and assumed to be typical of cable installed on the system. A disturbing number showed dielectric losses at rated voltage and 80 degrees centigrade of more than 5 watts per foot with isolated cases going to more than 10 watts per foot. Careful study of the operating records failed to disclose any evidence indicating previous high operating temperatures, nor was there any clue to the cause of the large increase. Some day, we hope to know the answer but until we do, it will be necessary to use some caution in calculating possible maximum temperatures or else be willing to accept the inevitable failure that will occur if a piece of this deteriorated cable happens to come at a point where the duct temperatures are somewhat higher than average.

F. H. Buller (General Electric Company, Schenectady, N. Y.): The writer wishes to endorse Mr. Thomas' conclusions most heartily.

The first conclusion is self-evident.

With regard to the second conclusion, the company with which the writer is associated has always contended that the most economical type of duct construction is a bank two ducts wide and deep enough to accommodate as many cables as may be required. Mr. Thomas has brought out in his paper that the use of duct banks with inside ducts is seldom economical, thus bearing out this contention.

With regard to the third conclusion, the company with which the writer is associated has always contended that the use of more than 12 cables in a duct bank is seldom economical. Mr. Thomas' curves, particularly figure 9, indicate that it is seldom economical to use more than 10 cables in a duct bank, even with a comparatively high-cost subway. While the inclusion of the cost of losses might increase this number of cables somewhat on the basis of annual charges, the writer is in full agreement with Mr. Thomas that a highly congested duct system is liable to be quite uneconomical in the matter of current-carrying capacity.

With regard to the fourth conclusion, this also has been the contention of the company with which the writer is associated, since the sacrifice of load on the higher-voltage cable may quite often exceed the total load carried by the low-voltage cable, and even if it does not, and the total load carried by the duct bank is increased by the installation of the low-voltage cable, nevertheless there may well be a definite sacrifice in economy by following this procedure.

With regard to appendix I, Mr. Thomas has followed the Kirke method of calculating cable ratings. This method is somewhat more complicated than the usual method adopted by the Edison Electric Institute and the Insulated Power Cable Engineers Association in preparing current loading tables, but as used by Mr. Thomas would not give widely differing results.

On the one hand, Mr. Thomas uses an ambient temperature for New York City of 15 degrees centigrade, whereas the usual method would be to base calculations on an ambient of not less than 20 degrees centigrade, on the basis of the curve of earth temperature shown in figure 14 of Mr. Kirke's paper (AIEE JOURNAL, October 1930, page 855). On the other hand, the usual method omits the heating constant H_0 altogether, or rather includes it in the duct constant D. In general, the usual duct-heating coefficient tends to be somewhat lower than Mr. Kirke's values, especially for small numbers of cables in the duct bank, and this offsets the difference in ambient. The resulting differences in current carrying capacity are shown in tables I and II of this discussion.

It will be seen that the usual method gives somewhat higher current-carrying capacity than the Kirke-Thomas method for small numbers of cables in the duct bank, but that the discrepancies involved are not very large.

With regard to the graphical method for evaluating current-carrying capacity when two different types of cables are installed in the same duct bank, the plan which Mr. Thomas outlines in his paper should work very well if the duct bank contains a group of cables which are not fully loaded, and it is desired to find how much load an additional group of cables can carry without exceeding permissible operating temperatures. It appears, however, to be limited to two types of cables, and involves a considerable amount of cut-and-try if it is desired to determine what load each group of cables should carry in order to operate at its maximum permissible copper temperature.

The writer has developed a graphical method which can be used quite readily for any number of different types of cable, and which will give the load which each cable can carry when operating at its maximum permissible copper temperature, or any other arbitrarily selected copper temperature, without resorting to cut-and-try. Since the method is very simple to apply, it might be well to outline it here.

Table I. Cables and Duct Arrangements Covered in Mr. Thomas' Paper

Number of Cables in Duct Bank	*Ratio
4	108
10	101
18	96

* Ratio of $\dfrac{\text{current rating by usual method}}{\text{current rating by Kirke-Thomas method}}$

Table II. Usual Standard Groupings

Number of Cables in Duct Bank	Ratio
1	1.12
3	1.09
6	1.05
9	1.02
12	0.99
*15	0.97
*18	0.96

* These groupings are not standard, but are obtained by extrapolation using the standard method

LIST OF SYMBOLS

T_c = copper temperature, degrees centigrade, equally loaded cables
T_{cn} = copper temperature of cable n (unequally loaded cables) in degrees centigrade
T_0 = earth ambient, degrees centigrade
T_d = duct temperature rise in degrees centigrade
W = loss per cable, watts per foot (for similar equally loaded cables)
W_n = loss in cable n in watts per foot (for unequally loaded cables)
L = loss factor, as a decimal (for equally loaded cables)
L_n = loss factor, as a decimal in cable n (for unequally loaded cables)
N = number of cables in duct bank
H = duct heating constant
D = "duct constant" for equally loaded cables = HLN
R_{in} = thermal resistance of insulation, for cable n
R_{sn} = thermal resistance of surface for cable n
R_i = thermal resistance of insulation (similar equally loaded cables)
R_s = thermal resistance of surface (similar equally loaded cables)

The usual equation for equally loaded cables is:

$$\begin{aligned} T_c - T_0 &= W(R_i + R_s + D) \\ &= W(R_i + R_s) + WLNH \end{aligned}$$

Or, since $WD = WLNH = T_d$

$$T_c - T_0 = W(R_i + R_s) + T_d \tag{1}$$

If there are N equally loaded cables:

$NWL = (WL + WL + WL \ldots)$ to N terms

which may be written

$$\sum_{n=1}^{n=N} nWL$$

Now, suppose that the N cables are unequally loaded but the average value of the product (watts loss times loss factor) is equal to WL. The duct temperature T_d will be the same as before.

Then

$$NWL = \sum_{n=1}^{n=N} nW_nL_n$$

for the unequally loaded case.

So that the duct temperature, T_d, which is the same as before, will be

$$T_d = HNWL = H\sum_{n=1}^{n=N} nW_nL_n \tag{2}$$

Also, from equation 1

$$T_{cn} - T_0 = W_n(R_{in} + R_{sn}) + T_d \tag{3}$$

or

$$W_n = \frac{T_{cn} - T_0 - T_d}{R_{in} + R_{sn}} \tag{4}$$

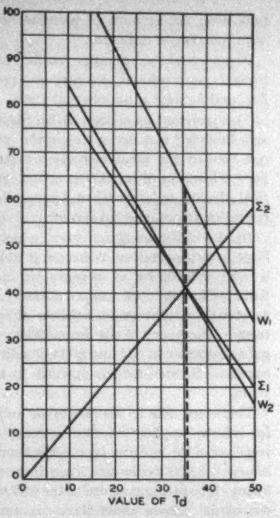

Figure 1. Illustrating graphical method of assigning current ratings to dissimilar unequally loaded cables in the same duct bank

Also, from equation 2

$$\sum_{n=1}^{n=N} nW_nL_n = \frac{T_d}{H} \qquad (5)$$

And, finally, from equations 3 and 2,

$$T_{cn} - T_0 = W_n(R_{in} + R_{sn}) + H\sum_{n=1}^{n=N} nW_nL_n \qquad (6)$$

Assuming arbitrarily chosen values of T_d, plot W_n against T_d from equation 4 for each cable. The quantity W_nL_n should be calculated for each value of W_n, and the summation

$$\sum_{n=1}^{n=N} nW_nL_n$$

should be computed and plotted for each value of T_d. Call this summation $\sum_1$.

Next, compute

$$\sum_{n=1}^{n=N} nW_nL_n$$

from equation 5. Call this quantity $\sum_2$ and plot it against T_d. Where the curves of $\sum_1$ and $\sum_2$ intersect, we have the value of T_d which satisfies both equations 3 and 5.

By dropping a perpendicular from this intersection and noting where it intersects the curves of W_n against T_d, we can find the values of W_n for each cable corresponding to the proper value of T_d, and we can determine the current loading to give these values of W in the usual way.

Since all the curves involved are straight lines, only two points need be calculated on each curve. This makes the arithmetical work very simple, even where several different types of cable are involved.

EXAMPLE

Two-by-five duct bank—five three-conductor 500,000-circular-mil 27-kv cables, five three-conductor 800,000-circular-mil 13.6-kv cables.

Here we will take $R_{in} + R_{sn}$ as equal to Mr. Thomas' values of $(H_1 + H_2 + H_3) \times 0.85$ and $H = H_4 + H_5$. The usual EEI-IPCEA values could, of course, just as well be used. The loss factor L_n will be taken as 40 per cent or 0.4.

	Cable		
	27 Kv, 500,000 Circular Mils	13.6 Kv, 800,000 Circular Mils	Notes
$R_{in} + R_{sn}$	2.902	2.53	Using lowest value of H_3
T_{cn}	74.4	82	
W_d	1.3	0.8	Dielectric loss
L_n	0.4	0.4	
T_0	0.15	15	
H	0.857	0.857	

Since there are two groups of five similar cables each, it will only be necessary to plot two curves of watts loss, since the cables in each group will presumably be loaded equally, though the two groups will carry different loads.

The values of W_1 and W_2 and also $\sum_1$ and $\sum_2$ are plotted in figure 1 of this discussion. $\sum_1$ and $\sum_2$ intersect at T_d = 35.4 degrees centigrade (duct temperature 50.4 degrees centigrade). W_1 = 62.5 or 12.5 watts per foot of cable. W_2 = 41.5, or 8.3 watts per foot of cable. $W_1 + W_2$ = 104.0. Mr. Thomas' method gives W_1 = 64.5 and W_2 = 44.0, or a total of 108.5 watts per foot of duct bank. The difference is probably due to slide-rule work or graphical discrepancies.

Both this method and Mr. Thomas' method are based on the assumption that the duct heating coefficient is the same for all the cables in the duct bank. This assumption may not hold very closely if some cables are installed in inside ducts. A conservative plan would be to assume a duct heating coefficient for all the cables corresponding to inside ducts; or alternatively, an average duct heating coefficient for the entire duct bank may be used, and the rating for the cables in the inside duct subsequently reduced somewhat, to take care of the higher duct-heating coefficient, which actually obtains in these ducts.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): This paper was interesting and stimulating. However, some of the conclusions apparently do not apply for Chicago conditions.

As a result of detailed cost studies, we have found that the cost of duct banks that are two-wide is higher per outside duct than for a duct bank that is three-wide, prorating the cost of manholes in each case. This applies to a two-by-four duct bank as against a three-by-three duct bank, as well as to a two-by-five duct bank as against a three-by-four duct bank. Generally, the width of excavation in Chicago is about the same for a three-wide conduit as for a two-wide conduit, due to the minimum requirements for working room, while the need for going to extra depth with two-wide conduits results in more labor and interference with other substructures. Another advantage to us in using the three-wide conduits, where there are enough cables involved to justify such conduits, is that the center ducts may be used for signal or relay cables without interfering with the use of the other ducts for power cables.

Our studies of heating constants indicate that a 9-duct conduit has a very slight advantage over the 8-duct conduit, and this applies also for 12-duct conduit as compared to 10-duct conduit, assuming that only the outside ducts are occupied for power cables.

In general, it seems there must be some differences in conditions between New York and Chicago in this matter.

Regarding the author's conclusion 3, we have been endeavoring to limit the size of our conduits to 12 ducts, or to 16 ducts in special cases, for at least the past 12 years.

In general, we have not found it uneconomical to install cables of different voltage classifications in a common conduit. If one were to lay out a brand new system and install all the cables in a given city in a short time, then it certainly would be most economical to install cables of only one voltage classification in a given conduit as far as possible. Our policy is to avoid as much as possible the installation of conduits in a street for five years after it has been repaved. These and other factors affecting system planning plus the fact that the incremental cost of the larger conduits is relatively small mean that many ducts are unoccupied. It therefore becomes necessary to use these ducts as much as possible for new circuits, regardless of the voltage.

It so happens, however, that this practice works out fairly well because it is frequently necessary to limit maximum conduit temperatures to 50 degrees centigrade or less, in order to avoid drying of the soil which would cause conduit and cable temperatures to become excessive. By limiting the normal conduit temperatures to 45 or 50 degrees centigrade, the resulting copper temperatures are reasonable in almost all cases for all types of cable that may happen to be in a given conduit. In connection with emergency loading, only one cable, or three cables in the case of a single-conductor, three-phase line, is subjected to an unusual load and is generating an unusual amount of heat. The emergency lasts just one day, except that it might last two days for an oil-filled line, but during that short time the increase in the temperature of the conduit is only a few degrees. At the same time the cable temperature may safely go to 90 or 100 degrees centigrade or so, that is, to the limit set by the insulation for emergency operation.

E. R. Thomas: It is gratifying to the author that the presentation of this paper should have aroused the interest indicated by the pertinent comments and discussions which have been presented.

W. F. Davidson calls attention to the

fact that the dielectric loss of cables withdrawn from service has been found to exceed the average values used in calculating the ratings for the paper in many instances. This is a fact which should be considered in any investigation of a specific duct loading problem. Its effect on the results will be to indicate that the greatest economy can be obtained with smaller duct structures when and if such high-loss cables are used.

Mr. Halperin's comment on conditions in Chicago is very interesting. It would seem that where a requirement for duct space for supervisory or signal cables exists, a very real economy might be obtained by the use of the three-wide rather than the two-wide duct structure.

Mr. Buller's general agreement with the conclusions of the paper is appreciated. The variations he mentions between the ratings obtained by the EEI method and the Kirke method are recognized. However, it is felt that a somewhat greater complication of the Kirke method gives greater accuracy than the EEI method does.

Mr. Buller's comment on the graphical method given in the paper suggests that it involves the use of cut and try. By the superposition of several curves drawn on different sheets of transparent material, it is possible to determine accurately the load which each of several cables will carry when all are operating at their maximum permissible copper temperature. With some loss of accuracy, it is possible to use the same curves to determine the load each of several types of cable will carry when operating at temperatures other than the maximum permissible temperatures. The method outlined by Mr. Buller does not appear to be as flexible as the one shown in my paper since one set of curves is good only for one solution of one set of conditions. A simultaneous solution of two equations would accomplish the result with less labor. The W_1 curves shown in figure 1 of Mr. Buller's comments are straight because his R_s is a constant. In my equation H_s replaces the R_s in Mr. Buller's equation and H_s varies with the watts lost.

The supplemental data presented by Mr. Comly are interesting since they indicate the probability that the conclusions given in my paper would not be affected materially by normal changes in type of load or average loading.

Mr. Komives' comment on the permissible temperature limit for oil-filled cable seems irrelevant since the figures in table IV are based on the allowable temperature for each of the cables indicated. For the 132-kv cable, the values are those for oil-filled insulation.

In closing, let me re-emphasize the fact brought out by the paper that a considerable saving may be realized by careful analysis of the economies involved in duct-bank size and loading in advance of construction. I am indebted to the discussers for their interest and hope that more analyses of the subject may be made as a result of this discussion.

Ignitrons for the Transportation Industry

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NONMEMBER AIEE

THE USE of the multianode metal-tank mercury-arc rectifier is well established in the transportation industry. At the present time there are approximately 500,000 kw of these rectifiers in operation on railway properties in America. The units vary in size from 500 to 3,000 kw and range from 500 to 3,000 volts direct current.

The mercury-arc rectifier has replaced rotating conversion equipment for transportation service largely because of its higher efficiency, particularly at low loads, lower installed cost, increased reliability, less maintenance, simpler control, no noise or vibration, ability to carry short-time heavy load swings, and its instant availability for service.

Although, for these reasons, the conventional rectifier amply justifies itself, it has been realized that it does not take full advantage of the possibilities inherent in the mercury-vapor arc. The voltage drop in a simple, high-current mercury arc is less than ten volts and the reverse voltage that such a structure will withstand is many times the value encountered in the transportation field. However, in some as yet not fully understood manner, a simple mercury-arc arrangement has been found to break down occasionally in the reverse direction or arc back, at voltages in the range required. In the conventional multianode rectifier, the anodes are removed from exposure to the cathode and are surrounded by shields and grids in order to provide the necessary reliability. This complication of the structure results in an arc drop varying from 20 to 30 volts, depending upon the tank size, the amount of increase being in proportion to tank size.

Figure 1 shows a cross section of a typical conventional mercury-arc rectifier, and figure 2 is an external view.

The ignitron, as conceived by Slepian and Ludwig,[1] is a major step in the progress toward the ideal mercury-arc rectifier. This type of rectifier is now a practical device as established by excellent operation in commercial service.

In the coal-mining industry, which is largely transportation, there are installed a total of 6,000 kw of mercury-arc rectifiers. Of this total, approximately 50 per cent, or eight units, consists of ignitrons. They vary in size from 300 to 400 kw and operate at 275 and 600 volts direct current. Service ranges upward to two years.

There are now in service or on order, for railway application, two mercury-arc rectifiers of the ignitron type. These units are each 3,000 kw in size, they have the heavy-duty rating, and are in the 600-volt d-c class. These units have an anode rating equal to that of the largest multianode rectifier now built for railway service. One of these units is for service on the subway system of the Board of Transportation of the City of New York, and the other is for service on the main-line electrification of the New York Central Railroad.

Principle of the Ignitron

A cathode spot is the essential element of an arc. With a cathode spot, in a low-pressure gas chamber, any anode will pick up current when a positive potential is applied. Since a cathode spot cannot be created reliably in a low-pressure gas by the application of high voltage, it is necessary to start a rectifier by some other means. In the conventional rectifier, this is done by drawing an arc by separating electrodes at the cathode surface. The cathode spot thus formed is maintained continuously by a small current to an auxiliary anode. This arc current results in ionized gas. It is obvious that economy of equipment and auxiliary power is effected by placing several power anodes in the same tank. This is the reason for the multianode rectifier. The continuous presence of ionized gas, which includes the time that the anodes are bearing reverse voltage, greatly facilitates the formation of a cathode spot on an anode which is the principal reason for the shields and grids as previously mentioned.

The ignitron principle provides a method of starting an arc reliably in a few microseconds. This method is ame-

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1. For all numbered references, see list at end of paper.

nable to synchronous application. With such a system of ignition, the arc may be permitted to extinguish completely at the end of each conducting period. This leaves the anode surrounded by deionized gas during the time that it is bearing reverse voltage, except for a few microseconds following the conducting period, which is the transition time required for deionization to take place. Of course, in order to take advantage of this method of operation, each anode with its own cathode is mounted in a separate chamber, thus removing it from the influence of other anodes when they are conducting current. This permits the reduction of the shields and grids to the minimum necessary to take care of the transition period and permits the location of the anode close to the cathode.

The way in which an arc is started by the ignitron principle is described in detail by Slepian.[2] Briefly, when a high-resistance rod is immersed in mercury and a current of sufficient magnitude is passed through the rod to the mercury, the potential gradient set up at the junction between the two materials is sufficient to initiate a cathode spot. The magnitude of current necessary is dependent upon the resistivity of the material used for the rod. It has been found that rods or ignitors of boron carbide or silicon carbide, which are the materials most in use today, have a resistivity such that a current of less than 20 amperes and approximately 100 volts are required. These are convenient values for practical operation. The excitation circuits will be described in a later section.

Construction of the Ignitron

In general, the type of construction used for large power ignitrons is the same as that used for conventional rectifiers. The anode assembly, consisting of a vacuum-tight insulating bushing, anode head, and the current-conducting parts is identical. The tanks are made from specially selected sheet steel with the seams welded vacuum tight. The same type of vacuum-tight gaskets are used for the cover-plate seal and for all separable connections in the vacuum pumping system. The vacuum pumping equipment is identical. The essential differences lie in the separate anode with associated cathode vacuum chamber, the vacuum-pumping manifolding, the simplified anode-shielding structure, and the ignitor with associated control thyratrons of the excitation system.

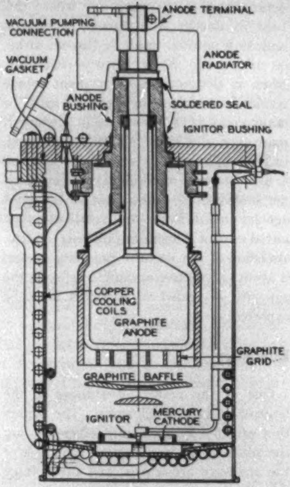

ANODE TERMINAL
VACUUM PUMPING CONNECTION
VACUUM GASKET
ANODE RADIATOR
ANODE BUSHING
SOLDERED SEAL
IGNITOR BUSHING
COPPER COOLING COILS
GRAPHITE ANODE
GRAPHITE GRID
GRAPHITE BAFFLE
IGNITOR
MERCURY CATHODE

Figure 3. Cross-section view of an ignitron

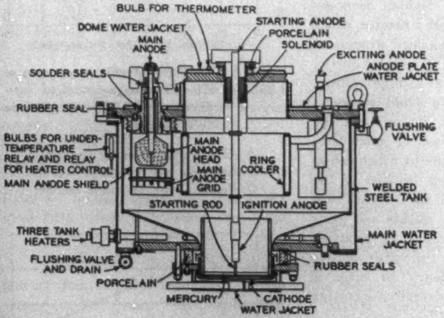

BULB FOR THERMOMETER
DOME WATER JACKET
MAIN ANODE
STARTING ANODE
PORCELAIN
SOLENOID
EXCITING ANODE
ANODE PLATE WATER JACKET
SOLDER SEALS
RUBBER SEAL
FLUSHING VALVE
BULBS FOR UNDER-TEMPERATURE RELAY AND RELAY FOR HEATER CONTROL
MAIN ANODE HEAD
RING COOLER
MAIN ANODE GRID
MAIN ANODE SHIELD
WELDED STEEL TANK
STARTING ROD
IGNITION ANODE
THREE TANK HEATERS
MAIN WATER JACKET
FLUSHING VALVE AND DRAIN
RUBBER SEALS
PORCELAIN
MERCURY
CATHODE WATER JACKET

Figure 1. Cross-section view of conventional multi-anode mercury-arc rectifier

Figure 2. A 750-kw 600-volt six-anode mercury-arc rectifier

Figure 3 shows a cross section of an ignitron.

There are a number of features associated with the small vacuum tank that contribute to reliability in service. The vacuum-tight gaskets are smaller. The need for a cathode insulator is eliminated. Copper coils for the water-cooling system are easily applied. The use of copper for external cooling coils and nickel for internal cooling coils eliminates all ferrous materials from the cooling system and reduces the corrosion problem to a minimum.

In order to secure a satisfactory wave form, power rectifiers are usually built with multiples of six anodes. This practice is followed in assembling the ignitrons into units. While, if required, more than six ignitrons can be assembled with a common vacuum-pumping system, greater operating flexibility is permitted, even for large station capacities, when the units are sectionalized.

Figure 4 shows a rectifier unit of six ignitrons.

A great deal of work is now being done on sealed-off rectifiers of both the conventional and ignitron types. So far, sealed-off construction has been confined to relatively small sizes, smaller than the usual transportation requirement. Not enough experience has been obtained to determine the average life of such rectifiers and it is obvious that this factor will determine the maximum size where this type of design is attractive. Since a sealed-off rectifier must be thrown away, or undergo a major factory rebuilding when it deteriorates to a point where service is unsatisfactory, the life must be many years to justify its use in the larger, more expensive sizes. On the other hand, in the small capacity sizes where the cost is low, the cost of periodic replacement is not prohibitive. This must be balanced against maintenance and relatively high initial cost of a vacuum-pumping system. Omission of the vacuum-pumping system is always attractive and an increase in the capacity of sealed-off rectifiers is to be expected.

Efficiency

One of the major advantages of the ignitron is its high efficiency. The factors that affect a rectifier unit efficiency are the losses of the transformer, the losses of the auxiliary apparatus, and the voltage drop in the power arc. The transformer is a highly developed piece of equipment and the losses are established by the economics of design. There is not much margin here on which to work to improve unit efficiency. The auxiliary losses are low and their total elimination would not represent much gain for units of the size used by the transportation industry.

The arc loss of a conventional rectifier constitutes not only two-thirds of the total unit loss but is known to be greatly in excess of that theoretically necessary. The present commercial ignitron, with its arc drop of 14 to 18 volts, is a major advance toward the theoretical minimum from the 20 to 30 volts obtained in the conventional design. In both ignitrons and multianode rectifiers the higher arc drop is associated with the higher ratings.

Figure 5 illustrates the efficiency advantage of the ignitron over conventional rectifiers at 600 volts.

For 275-volt applications, the ignitron has an even more marked advantage in efficiency. In any given type of rectifier the losses are almost proportional to the current and the arc drop is only slightly influenced by the system voltage. Therefore, the arc drop is a greater proportion of the output voltage in the lower voltage classes and an arc drop advantage becomes more important. This is illustrated in figure 6.

Factors Influencing Rating

The major factors which determine the rating of a given design are thermal limit, current instability in the arc, and arc-back frequency.

The thermal limitations of materials used are easily determined and offer no problems from the design standpoint.

Arc-current instability is the cause of voltage surges. In order to transport a given current in an arc, proper ion density must be maintained. The lower the vapor density, which is influenced by the temperature of the cooling surfaces, and the more obstructions in the arc path, the more difficult it is to maintain proper ion density. With an inadequate supply of ions, the arc resistance fluctuates with corresponding current fluctuations, or the arc tends to go out. Sudden decreases of direct current through a reactor, which in this case is the secondary winding of the transformer, cause the stored energy of the reactor to appear as high voltage, or voltage surges. To avoid surges in conventional rectifiers, it has been the practice to maintain cooling-water temperatures above the value at which surges occur. In the ignitron, because of the reduced obstructions in the arc path represented by minimum shields and grids and because of the proximity of the anode to the cathode, where the vapor density is greatest, the tendency to surge is greatly reduced. Incidentally, operating conditions under which surges occur also favor the occurrence of arc-backs. This cause of arc-back is, therefore, materially decreased in ignitron rectifiers.

The most important of the limitations in the design of a rectifier is arc-back. Although the causes of arc-back are not fully understood, they are known to be favored by such things as impurities in materials and foreign dirt particles, poor vacuum, too high mercury-vapor density, surge conditions, and exposure of an anode bearing back voltage to a cathode spot or ionized gas. The first three of these causes are minimized by careful selection of materials, careful shop practice, use of modern vacuum technique, and adequate cooling-medium control. Surge-producing conditions are avoided for normal conditions of operation.

As previously mentioned, the last cause is minimized by the use of shields and grids, and for the conventional rectifier, by the removal of the anodes from the cathode. These shields and grids increase the arc drop and the amount of the increase is proportional to the extent to which the arc-back rate is minimized. Experience with conventional rectifiers in commercial service has established the economic balance between the permissible arc-back rate and efficiency, as influenced by arc drop. Since the ignitron has per-

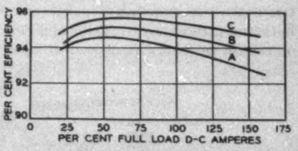


Figure 5. Rectifier unit efficiency curves of 3,000-kw 600-volt voltage-controlled mercury-arc rectifiers with 13,200-volt 60-cycle supply

A—Single-tank 12-anode rectifier
B—Sectional-type 24-anode rectifier
C—Ignitron-type 12-anode rectifier

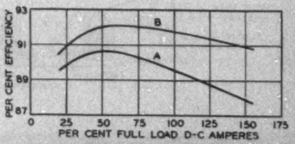


Figure 6. Rectifier unit efficiency curves of 600-kw 275-volt voltage-controlled mercury-arc rectifiers with 2,300-volt 60-cycle supply

A—Single-tank six-anode rectifier
B—Ignitron six-anode rectifier

Figure 4. A 1,500-kw 600-volt six-ignitron rectifier unit with vacuum and control auxiliaries

mitted a substantial reduction in shields and grids as well as anode to cathode spacing, by an entirely new principle of operation, there is a new proportionality between arc-back frequency and arc-drop voltage. At present, because there is this new proportionality, in order to provide greater freedom from arc-back, full advantage of the efficiency increase has not been taken.

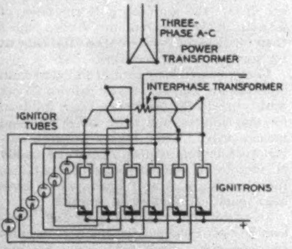


Figure 7. Ignitron rectifier diagram using the anode firing method of excitation without voltage control

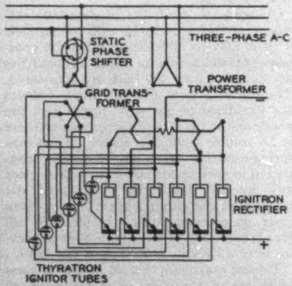
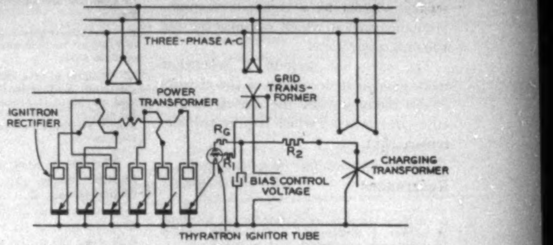


Figure 8. Ignitron rectifier diagram using the anode firing method of excitation with voltage control by phase shift

Special Circuits for Ignitrons

There are several ways by means of which the necessary accurately timed current impulses may be applied to ignitron ignitors. Possibly the simplest is shown in figure 7, which uses anode firing without direct-voltage control. The ignitor power is taken from the main transformer through thermionic-cathode gas-filled ignitor tubes. When the anode of the ignitron and associated ignitor tube become positive with respect to the cathode, current will flow through the ignitor tube because of its thermionic cathode. Upon the creation of the ignitron cathode spot, caused by this flow of current through the ignitor tube and ignitor, the ignitron will pick up, its arc short-circuiting and therefore extinguishing the ignitor current.

Figure 9. Diagram of a capacitor firing method of excitation



Control of the direct voltage of an ignitron is obtained in the same manner as it is for the conventional rectifier, that is by delaying the pickup of the anodes. However, in the ignitron, this delayed pickup is controlled by the provision of energized grids in the ignitor tubes rather than in the main power arc. This permits voltage control without any sacrifice in efficiency and by the use of relatively very little control energy. Figure 8 shows the devices and circuits involved. Thyratron ignitor tubes, which are thermionic cathode tubes with control grids, are used for the ignitor circuits. The anodes of the ignitron and thyratron tubes become positive with respect to the cathode, as before, but current will not flow through the thyratron tube until its grid is made positive with respect to the cathode by the grid transformer. The grid transformer is energized through a static phase shifter by means of which the phase angle between the potential of the anode and that of the grid may be accurately controlled. In this manner, the formation of the cathode spot in the ignitron is delayed to secure the desired direct-voltage reduction.

Another method of ignitron excitation is shown in figure 9, in which the ignitor current is obtained from a separate source including capacitors and a charging transformer. In the circuit shown, direct-voltage control is obtained by means of a bias voltage in the neutral of the grid transformer rather than by means of a phase shifter.

Other methods of ignitron excitation include transformer without capacitors, peaking transformer with Rectox, rotating impulse generator, and rotating commutator. The last three methods do not require ignitor tubes.

Since the ignitron depends on current flow through its ignitor before an anode can pick up, it is only necessary to block the excitation current to prevent pickup. This blocking can be accomplished either by opening the ignitor circuits, which can be done by relay contacts, or by applying a negative voltage to the grids of the thyratron tubes, if used. Since this involves only the control of low-energy circuits or the blocking of grids of low-energy tubes, "arc snuffing," that is, the interruption of d-c short circuits or of anodes feeding into an arc-back, can be accomplished with great speed and reliability.

Conclusions

The ignitron rectifier brings to the transportation industry a conversion unit having several advantages over the conventional multianode rectifier.

Although, in the interest of high reliability, full advantage is not taken of the possible reduction in arc drop, an efficiency advantage of from one to $1^{1}/_{2}$ per cent is realized for 600-volt units and of from 2 to 3 per cent for 275-volt units.

Because control of anode ignition is accomplished through small auxiliary tubes, voltage control is more flexible, has no detrimental influence on efficiency, and requires less control energy. For this same reason, "arc snuffing" can be accomplished with maximum speed and reliability.

Because the single-anode tanks of ignitrons are relatively small, the use of tubing of copper or other corrosion-resisting material for the cooling system is easy. This practically eliminates the corrosion problem.

In performing internal maintenance, only one ignitron need be opened at a time. The smallness and lightness of parts greatly facilitates this operation.

For a given rating, an ignitron unit is lighter and occupies less volume than a conventional rectifier. This results in economy of installation.

The ignitron also has some disadvantages.

There is the necessity for manifolding

separate tanks to a common vacuum-pumping system which complicates the vacuum connections.

The excitation system is somewhat more complicated. Most of the circuits in use today involve the use of thermionic-cathode tubes which require periodic replacement.

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Discussion

D. S. Smith (Northern Electric Company, Montreal, Que., Canada): In the paper on "Ignitrons for the Transportation Industry" the statement is made that as yet the sealed-off construction of rectifiers has been confined to small sizes below the range usually associated with traction substations. It is true that the individual sealed-off unit has not been built in large sizes, say above 1,000 amperes, but by the adoption of the unit principle large rectifier banks have been made possible. Glass is for many reasons an ideal material to use for the envelope of a sealed-off rectifier and the glass bulb rectifier has achieved considerable popularity in some parts of the world.

First of all let me give a rather broad picture by describing briefly some of the large glass-bulb traction installations made by one British company:

A. The Manchester-Bury line of the LMS Railway has two 3,600-kw rectifier substations operating at 1,200 volts direct current. The rectifier transformers are connected 12-phase and no d-c smoothing equipment is used. Each substation has three banks of six bulb units each, with high-speed d-c circuit breakers for each bank. These two substations are two of ten glass-bulb-equipped substations on the LMS totalling 13,200 kw.

B. The Bombay Baroda Railway in India has one 4,000-kw glass-bulb substation comprising two banks of six bulb units each, operating at 1,600 volts direct current. The rectifier, which is connected 12-phase, is provided with d-c smoothing equipment and has automatic grid control to give an overcompounded characteristic.

C. The New Zealand Government Railways have six substations with a total capacity of 6,000 kw operating at 1,600 volts direct current.

D. The British Columbia Electric Railway has two 330-kw substations and one 660-kw substation operating at 550 volts direct current. Their experience with glass bulbs has been the subject of an article in the technical press.

E. The London Passenger Transport Board has a total of 49 glass-bulb substations ranging in size up to 3,000 kw and having a total capacity of 35,500 kw.

F. The largest glass-bulb rectifier substation is one of 7,000 kw in Shoreditch London but this is not a traction job.

G. Finally, to give some idea of the place of the glass-bulb rectifier in Great Britain, I might say that the total installed capacity is over 500,000 kw against 350,000 kw of steel tank—these figures include all power rectifiers, not only those for traction service.

Now let us look at the glass bulb from another angle. In spite of its apparent frailty it can, if it is of approved type, be insured at an annual premium equal to $4^1/_2$ per cent of its value for the nine years following the initial year of service. During the first year it is covered by the manufacturer's guarantee. Mention has already been made of the Shoreditch station and it is interesting to note that no bulb replacements have been made to the three original 2,000-kw banks each with 16 bulbs and installed in 1929, 1930, and 1931, respectively. For a 2,000-kw installation made in 1925 the average annual maintenance cost per bulb unit including bulb replacements has been under $2.25 in spite of the fact that the bulbs are of an old type which could not be repaired. One engineer when asked about maintenance charges on a 3,600-kw traction substation under his charge placed them at about five shillings a week, $1.25, and this included the cost of periodical cleaning up of the substation.

Objections to the use of glass in the envelope of a rectifier are largely psychological and are gradually being overcome as a result of the comparative rarity of breakage in handling. One installation of glass-bulb rectifiers is in a mine in South Africa where the bulbs are subjected to frequent concussions from explosions. The British Admiralty actually carried out tests in which rectifier bulbs were set near large guns during firing and as a result have a glass-bulb rectifier at the Woolwich Arsenal.

Glass-bulb rectifiers are of course characterized by their extreme simplicity, the only auxiliary required being the cooling fan. The bulbs hold their vacuum indefinitely so that no vacuum pumps are required, and control gear is very simple in comparison with corresponding gear for water-cooled steel-tank installations. The strength of the glass bulb really lies in the seals which are simply formed by using a glass and metal combination with two nearly identical coefficients of expansion. The technique of glass manufacture, including of course, the seals, is the foundation for the success of the glass bulb, but it has taken long years to develop the technique and as a result the pioneer manufacture of bulbs in Great Britain still does a very large proportion of the glass-bulb business. There is one other point in connection with the use of glass which must be mentioned and it refers to its transparency. This is an invaluable asset both during processes of manufacture and afterward during operation. Trouble in a glass bulb when it does occur is very readily diagnosed.

Bulbs of the larger sizes are usually of the six-anode type with two or three excitation electrodes continuously energized and starting electrode. The old tilting bulb is a thing of the past and methods of starting are very simple, one method using a flexible electrode which is drawn down into the mercury pool by means of a small external electromagnet. Start-up is practically instantaneous and full load can be thrown on a cold bulb without fear of trouble.

The electrical characteristics of the glass-bulb rectifier are generally similar to those of the steel-tank type. Inherent regulation is usually about six to seven per cent from low load to full load. Efficiencies generally are higher with glass bulbs than for the large tank-type rectifiers as the use of large tanks involves a longer arc path with higher arc drops—the arc drop is of the order of 22 volts in the glass bulb and is thus higher than for the ignitron, but about the same as for small tank-type rectifiers.

Common overload ratings for glass-bulb rectifiers for traction service call for 25 per cent overload for two hours, twice full load for ten minutes, and three times full load momentarily. While higher overload ratings are sometimes called for and can readily be met by a small derating of the bulbs, these are fairly typical figures which have been found satisfactory in practice.

Six-phase connection of glass-bulb rectifiers is most common for traction supplies and smoothing equipment comprises air-cored choke and tuned shunt circuit. Twelve phase is sometimes used, two six-phase bulbs working together, and in such case smoothing equipment has usually been found unnecessary except where grid control was in use.

Backfires or arc backs in glass-bulb rectifiers are of extremely rare occurrence. This is easy to understand when the processes of manufacture by which all impurities are excluded from the bulb are considered. The use of a pure graphite anode reduces the likelihood of hot spots forming on the anode and as the vacuum is permanent there is no trouble from this source. High-rupturing-capacity fuses are normally connected in each anode circuit and these clear any internal faults but high-speed d-c breakers in the output circuit of each bank clear on external faults. Incidentally, all that is necessary to put a bulb back in service after a backfire is to replace the fuses.

Present maximum current ratings of glass bulbs are of the order of 400 amperes at 550 volts and 300 amperes at 1,500 volts, these ratings having been made possible by the efficient use of fan cooling. Experimental bulbs have been built to carry 1,000 amperes at the lower voltages and it would appear that a bulb of this rating would be useful for large installations if there is no sacrifice in efficiency.

Voltage control where required has in many cases been effected with induction regulators or on-load tap-changing transformers. Grid control has been very successfully applied but is not favored very generally on account of the harmonics introduced. Where grid control is used it is considered advisable to apply the debiasing voltage in the form of a steep-front wave, as the alternative method of steadily increasing the amplitude of the positive bias may lead to uncertain timing of the ignition of anodes working in parallel.

Multibulb banks of glass bulbs have the distinct advantage that the loss of one bulb results in only a small decrease in capacity. Further the large number of anodes results in a low current density per anode and this, together with the wide mechanical spacing of the electrode arms helps further to reduce the possibility of backfire.

While it would appear at first that the space required for glass-bulb rectifiers would be large this in fact is not the case. Generally speaking they require little if any more space than equivalent metal-tank types, this being partly due to the smaller amount of control gear necessary with glass.

Finally I would refer to discussions which have been going on with a view to eventually issuing an international specification on mercury-arc rectifiers. While it was originally proposed to have two separate specifications with different test conditions for steel-tank and glass-bulb rectifiers, as a result of the insistence of the glass-bulb manufacturers themselves the two are to be grouped together and the glass-bulb rectifier will thus have to meet the same standards as the steel-tank type.

J. J. Linebaugh (General Electric Company, Schenectady, N. Y.): The authors have given us a good outline of the development of the ignitron type of mercury-arc rectifier for transportation service with a general description of the ignitron principle, as applied to single-anode tanks.

The company with which the writer is connected has been working on the new problems incident to the development of this new type of rectifier for several years with very satisfactory results.

In 1937 the development had reached such a stage that an order was taken for a 3,000-kw 625-volt 12-tank unit for the New York Board of Transportation subway system. This unit has been in service since June 1938 and carries regular loads successfully. It is interesting to note that this unit must deliver 14,400 amperes for one minute. Similar equipment has been sold for service in coal mines.

One of the main problems to be solved in this development is the best method of starting the arc, as regards simplicity and reliability.

A number of different firing schemes have been proposed and several tried with varying degrees of success. Improvements are continually being made for the purpose of simplification and longer ignitor life.

It has been our experience that these 625-volt single-anode tanks can be opened for inspection and then restored to regular service without the necessity of bakeout if each tank is provided with a separate vacuum valve.

Our experience has been similar to that described in the papers and we find the advantages set forth in the conclusion of the paper are amply realized.

This type of rectifier will undoubtedly be a serious competitor of the multiple-anode tank.

S. R. Durand (nonmember; Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The authors of this interesting paper have reviewed the principle of the ignitron tube and compared it with the multianode rectifier tank which today is well established in the transportation industry. When new developments are created which appear to have advantages in comparison to equipment already in use, there is always a period of time in which the value of these new features must be carefully weighed against the ruggedness and reliability of the well-tried and proved equipment. Very often in spite of outstanding new features incorporated in a device, some of these features in themselves may have inherent limitations which will impair the ultimate development of the equipment to the same degree of service reliability as attained in the older equipment. As the development of ignitrons and similar electronic devices proceeds, it is possible that in the near future equipment will be perfected which will most nearly meet in all respects the qualities desired in conversion apparatus for the transportation and other industries.

The authors have described the method of control utilizing the principle of timing the ignition. However, they also mention that use is made of shields and grids in ignitron tanks, and a grid and grid-inlet bushing connector are shown in the cross-sectional diagram of figure 3. It would be interesting to know if grid control is employed in some manner with ignitor control, or if the grid is simply energized to assist in the pick-up of the arc.

The use of external copper and internal nickel cooling coils is preferable to the use of steel water jackets on small tanks even though the problem of corrosion has been materially reduced in most large rectifier installations by means of recirculating cooling systems with heat-exchange units. In some localities the cost of cooling water is an important item in the operation of rectifiers in the transportation industry, so that it would undoubtedly be of interest to many engineers to know if the cooling-water consumption of a group of ignitrons can be reduced in comparison to multianode tanks under the same load conditions.

O. K. Marti (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The authors present in a very interesting way the principle of the so-called "ignitrons" consisting of a tube or tank with a single anode having a cathode and an ignition device called the "ignitor," from which this kind of rectifier took its name. A very instructive comparison is made between the design as well as the characteristics of this rectifier with a conventional multianode rectifier which today is well established in the transportation field.

The main feature of operation of this rectifier is to establish a cathode spot only for a very brief interval so that no arc is maintained during the time a reverse voltage is applied to the anode. Therefore no ionized gases will be present during this period and it is claimed this principle will result in an operation free of backfires. At least the original papers by Mr. Slepian elaborated on this theory and pointed out that this new principle of inducing an anode to fire would reduce the backfire tendency even though the anode is located directly above the cathode and not shielded by grids, baffles, or the like.

Therefore I was greatly astonished to notice from the cross-section view of such a rectifier (see figure 3) that not only is the same anode arrangement with shields used as in the conventional multianode rectifiers (see figure 1), which the authors call "an elaborate one," but the same ring insulator to hold the anode shield and a very complicated grid and shield with two baffles and a cathode with an ignitor. By comparing figures 1 and 3 these facts become apparent. Considering that for a 12-tank arrangement there are 12 ignitors and 12 cathodes instead of one as in the conventional type of rectifier, it, therefore, seems to me that the authors overstress the simplicity of this new rectifier design. The same comparison could be made considering the number of auxiliary devices for the ignition apparatus of both types, however, reference is made to figures 7, 8, and 9, each showing as many ignition and auxiliary devices as there are tanks.

The brief presentation about surges is very interesting and our observation on an ignitor-type working together with a conventional-type rectifier, when both were cooled with water at three degrees centigrade, showed the former to operate without any surges originating in the main arc. However, what was most surprising was that a great many surges were found to be originating in the ignition arc. It is not our experience that surges due to an unstable arc lead to backfires; several 3,000-kw units on the Long Island Railroad which were installed from six to ten years ago were subjected to numerous surges during the winter season because the cooling water was often below ten degrees centigrade during starting. There are, however, other reasons which made our company introduce recoolers in order to avoid having water of very low temperature enter the rectifier, as is the case when direct cooling is used. The same reasons would in some cases also necessitate a recooling system for these single-anode tank ignitor rectifiers.

I understand that not only is the life of these ignitors very short, probably due to the fact that the main arc in each cycle is for an instant concentrated at the base of the ignitor, but that these ignitors fail quite often, during normal operation, to establish the main arc, and one or more anodes and their respective transformer windings refuse to carry current for several cycles. In other words, every time an anode of a 6- or 12-phase transformer rectifier circuit fails to pick up current, the 6- or 12-phase transformer is magnetically unbalanced. It was a surprise to me to see ignitor rectifier installations where no precautions were taken to avoid the destructive effect of such abnormal operations. These effects may not yet be apparent since these rectifier installations are operating below full load and have not been in service very long. Frequent arc failures may affect the life of the secondary windings of the transformer, especially should such ignitor failures occur during heavy load.

It would have been very valuable if the authors could have given some data on how these ignitor rectifiers behaved during overload and what overload characteristics they show compared to the conventional multiple-anode rectifiers. Due to the lack of volume, the gases freed during overloads and the excess vapor pressure produced may have a very decided effect on the overload capacity of such small tanks.

It would have been very interesting if the authors could have made some comparison between the conventional multiple-anode rectifier tank, the sectionalized multiple-anode rectifier, and the ignitor single-anode tank, not only as to arc drop or efficiency, but also in regard to auxiliary equipment, power consumption of auxiliary equipment, etc. This would have been very instructive because the same authors have fostered the introduction of sectionalized units—in other words, have repeatedly recommended the use of four multiple-anode tanks of 500- to 750-kw size instead of a 2,000-kw or 3,000-kw single-tank unit. All of you who have followed the rectifier development during the last few years will probably agree with me that the sectionalized rectifiers have not been used here nor abroad very extensively. Now this paper recommends the use of a further subdivision of units in tanks of single anodes. I do not want to infer that this may not be the final solution, but on the other hand I would like to call to your attention that the same optimism was expressed the last few years in regard to the sectionalized unit. Furthermore, we have to keep in mind that new features must be carefully weighed against the reliability of the well-tried and proved equipment.

J. H. Cox and G. F. Jones: Mr. Smith has presented some very interesting data on the capacities of glass-bulb rectifiers in service throughout the world and the bulb life being experienced with these units.

Bulb capacities up to 1,000 amperes are predicted, but it is interesting to note that the highest bulb capacity, for a commercial installation, listed in the discussion is 208 amperes. For large-capacity installations, this would indicate a large number of units with attendant complication and large space requirement. The overload rating standards listed in the paper are much lower than American standards for transportation service.

Glass is a poor heat conductor, which accounts for the very low capacity/volume ratio as compared with metal-tank rectifiers. Relatively large condensing surfaces are required in order to control the vapor pressure for given load conditions.

Except during the experimental stage, the ability to see what is going on inside the rectifier has little value. With modern relay applications, faulty conditions are easily detected and the cause exactly determined. With metal-tank rectifiers, any necessary repairs can be made on location by the regular maintenance personnel.

The glass-blowing art has not been developed in America to the point where large glass-bulb rectifiers can be made reliably. This makes any American user dependent on a European supplier. Contrary to Mr. Smith's statement, we are informed by a British user of glass-bulb rectifiers and by our European manufacturing associates that a regular setup is made for return of the glass bulb to the factory for re-evacuation, the user being supplied with special shipping cradles to minimize breakage during shipment.

For comparable service standards, the control functions for any type of rectifier are the same. Mr. Smith points out the simplicity of fuses in the anode circuits of glass-bulb rectifiers. This is simply an inexpensive device for localizing faults which could be used with any rectifier if service standards permit manual replacement of fuses.

Mr. Durand has asked regarding the energized grid in the ignitron illustrated and regarding comparative water consumption of the two types of rectifiers.

As used at present, the grid is connected to its associated anode through a resistor, in the large size ignitrons, to insure prompt pickup of the anode. It is not used for voltage control. This is so easily accomplished by control of the ignitor current that there is no need for controlled grids in the ignitron.

For given conditions of load and cooling-water temperature, the water consumption of the two types of rectifiers is comparable. The loss in the ignitron is lower, but for present designs, the discharge water temperature is also lower, the two factors practically counterbalancing each other so far as water requirement is concerned. Due to the use of copper cooling coils for the ignitron, except for very bad water conditions, a heat exchanger is not required to minimize corrosion. For direct water cooling, the water consumption is considerably less than for a unit requiring a heat exchanger.

Mr. Marti expresses surprise at seeing grids in an ignitron. As pointed out in our paper, a limited amount of shielding is used to take care of the transition period. As is natural with a new product, ample margin is taken in the use of these grids. It is expected that they will be reduced in the future. However, even in the present design, the amount of reduction of shielding can be realized by comparing the arc drop of 12-anode 3,000-kw 600-volt units. For the ignitron the figure is 18 volts and for the single tank design, approximately 30 volts. There is little likelihood of the shielding being reduced in the "well-established" conventional rectifier.

The relative simplicity of the anode structure of the ignitron cannot be realized by comparing figures 1 and 3. Figure 3 shows one anode of a 12-anode 3,000-kw 600-volt ignitron, whereas figure 1 shows one tank of a four-section 3000-kw 600-volt sectionalized rectifier which has a total of 24 anodes and which has by far the simplest anode structure of any rectifier at this rating. If a comparison is made with the anode structure of a 12-anode single-tank rectifier at this rating, for either grid control or nongrid control, the relative simplicity is quite pronounced.

The ignitron has a separate cathode for each anode. This cathode consists of a mercury pool in the bottom of the tank with a small quartz ring to confine the intermittent arc to the center of the pool. Note that there are no cathode insulators, no vacuum seals, no return mercury baffles, and no moving parts in the excitation system.

Mr. Marti's statement regarding ignitron circuit surges comes as a complete surprise to us. Surges in an arc originate when, for given conditions, the arc path is overloaded. If properly applied, the low-energy ignitron circuit of the ignitron will not surge nor will it be influenced by surges originating in an associated power arc. In the authors' experience, which comprises most of the past experience with ignitrons, there have been no surges in ignitron circuits.

The life of the ignitors is still to be determined. We now have over 100 ignitors in commercial rectifier service and have yet to experience a single failure of an ignitor in operation extending up to two years.

Pickup of an ignitron anode is just as reliable as for a multianode tank rectifier. For either type of rectifier, it is simply a matter of supplying the proper ionization to insure pickup. Ignitrons operate an inverter service with excellent reliability. Here, a single failure of an anode to pick up will result in a forward fire or short circuit. Extensive testing of both types of rectifiers in this service shows comparable reliability.

Failure of a thyratron excitation tube will result in failure of its associated anode to pick up. This results in magnetic unbalance of the transformer with tendency to saturate and with consequent increase in magnetizing current. The only result is increased heating of the transformer. This is a gradual temperature rise and is guarded against by transformer thermal protection. It could hardly be termed "destructive." An occasional failure of an anode to pick up is definitely of no consequence.

In actual railway service, a few failures of thyratron tubes have been experienced. The tubes have been replaced during normal inspection periods and in no case has any protective device been called upon to operate nor has service been impaired, even with tubes out of service for several days. Simple automatic means are available, if desired, to detect continuous misfiring of an anode.

The overload characteristics of the ignitron are equal to those of the conventional rectifier. Obviously they must be to meet the specified tests. They are somewhat superior in the higher, short-time overloads—above rating—because of the more open arc path and lesser tendency to surge.

The auxiliary power requirements are not an important item in determining rectifier efficiency. A vacuum pumping system requires less than one kilowatt and an excitation system for a tank rectifier or ignitron, three-quarters of a kilowatt or less. The efficiency curves shown in the paper include auxiliary power losses.

Contrary to Mr. Marti's statement, the sectional rectifier had an excellent reception following its advent, notwithstanding the fact that it was a new type in an established field. Since then, there have been as many sectional rectifier units installed in the transportation industry as single-tank rectifiers from any one supplier. The ignitron is receiving an even more gratifying reception.

Experience With Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines

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THE basic principles of ultrahigh-speed reclosing of high-voltage transmission lines have been presented previously before the Institute.[1] Although, as has been explained, the effects and phenomena behind these principles are generally known, there are still a number of unknown factors that have not been explored fully and the effects of which need be known to make a thorough and scientific application of these principles. Among these are further data on the effects of breaker time and elapsed time between clearing of the arc and the reenergization of the circuits on the deionization of the arc and the re-establishment of the insulation strength of the surrounding area; data on the probable extent of and total time elapsed, as well as time between intervals of multiple strokes; knowledge concerning the effects of the quantity and the type of load on the likelihood of restriking or the failure of lines to hold when re-energized by virtue of system drifting away from synchronism; and, finally, data on the dead time needed on phase to phase faults to prevent restriking.

All of these, however, are elements in a problem which can reasonably be expected to be further developed as time goes on. They are all aspects of a problem that on the whole is well understood and on which further work is going forward. But while waiting for results from this work to materialize, there is no reason why the admitted great advantages in power-system operation of utilizing the main principle need be or should be waived because the problem has not been worked out yet with complete precision. As a matter of fact the authors believe that there is no high-voltage line today, if it is of any importance, that should be designed and installed on any other basis except on the basis of ultrahigh-speed reclosing. Since the presentation of the first data on this subject, three additional line sections, that is six terminals, have been equipped with ultrahigh-speed reclosing and a number of others, as will be brought out later, are under way. It is the purpose of this paper to describe the development of the equipment and the installation of these new terminals and to cite operating experience with all of them in so far as that is available.

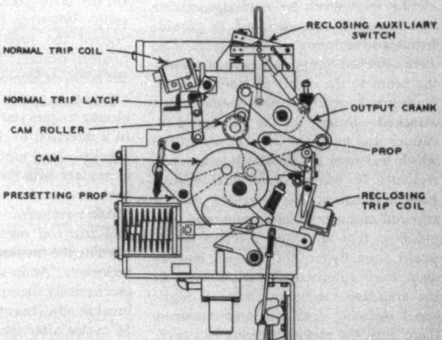

Figure 1. Schematic diagram of the new ultrahigh-speed reclosing mechanism for oil circuit breakers

The Elements of Ultrahigh-Speed Reclosing

The elements of an ultrahigh-speed reclosing setup are three. These are the high-speed breaker, the ultrahigh-speed mechanism and the high-speed relay system.

It is desirable that the circuit breaker be capable of interrupting a fault and deenergizing the line in the least possible time. So-called high-speed breakers available heretofore, in the United States at any rate, have had to utilize for this purpose a time of approximately eight cycles after the trip coil was energized. This does not refer to special designs. Within the last year more or less standard breakers having total time not to exceed five cycles have been developed and although faster times are expected, they are as yet not available today, in the American market at any rate. The work described herein has all been carried out so far on breakers having a time of approximately eight cycles.

The reclosing mechanism of the breaker has to be so designed that it is capable of reclosing the breaker with an elapsed time equal to no more than the minimum necessary to assure complete deionization of the arc and, therefore, assurance of no restriking on the one hand and minimum probability of loss of synchronism or loss of load on the other hand. Within the limits of eight-cycle operation of a breaker it has been felt heretofore that this time has to be of the order of a minimum of seven cycles but this has not been obtainable heretofore on mechanisms without running into stresses beyond what was desirable or practical in the standard breaker designs. As will be shown later on the actual performance so far this time has been from 10 to 14 cycles.

The relay system again must operate positively to clear the circuit on both ends in a minimum of time. Within the limits of breaker and reclosing speeds immediately in contemplation, it has been shown previously that this time should not exceed one cycle. No difficulty has been experienced so far in getting that with the utmost reliability.

In the earlier designs of ultrahigh-speed oil-circuit-breaker mechanisms two

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[1] For numbered reference, see end of paper.

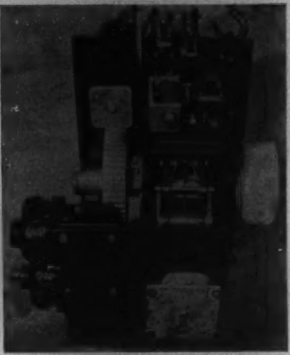


Figure 2. Front view of new ultrahigh-speed reclosing mechanism

mechanisms were provided for closing the breaker. One of these was a standard closing mechanism for normal operation and the other was designed to provide high-speed reclosing. These mechanisms were attached to opposite ends of a walking beam to the center of which the operating rod for the breaker contacts was attached. Energy for the high-speed reclosure was provided by a heavy spring which was reset automatically after each reclosure by means of a small motor. Each mechanism was provided with a trip coil and a transfer scheme was provided so that all tripping relays which would normally trip the reclosing mechanism were automatically transferred to the standard mechanism after a high-speed reclosing operation and remained there until the reclosing spring had been reset. The high-speed reclosing mechanism was also provided with an opening spring to speed up the opening of the breaker contacts. When the reclosing trip coil was energized this spring pulled the breaker contacts through a travel of about eight inches, at which point a latch released the closing spring, thus completing the reclosing operation. It was found that these mechanisms could be adjusted to give reliable operation with 18 cycles total elapsed time from trip coil energization to reclosure of breaker contacts.

Because there were two mechanisms required for each breaker, the total space needed for the complete equipment was considerably increased over that required by a standard electrically-operated breaker. Further, the space occupied by the high-speed reclosing part of the device was much greater than that used by the standard closing mechanism, so that the total space occupied by the complete equipment was more than doubled.

It was felt that this space requirement should be reduced if possible and at the same time the mechanism should be simplified in its operation. Keeping these objectives in mind, a new mechanism was designed and built which used the same motors both for normal closing and high-speed reclosing, thus eliminating the need for powerful reclosing springs, reducing the space required for the equipment, and considerably simplifying its operation.

A schematic diagram of the new ultrahigh-speed reclosing mechanism is shown in figure 1. As in the case of the earlier equipments these new mechanisms are provided with a standard trip coil and a high-speed reclosing trip coil. The closing motors drive a cam which operates the breaker output crank through a roller on its surface. At the end of the closing operation a prop falls into place and holds the breaker contacts closed. At the same time the cam is prevented from returning to the open position by the presetting prop. When the reclosing trip coil is energized the prop is removed and the breaker contacts begin to open. After the contacts have opened a predetermined amount, an auxiliary switch energizes the closing motors starting the cam revolving in a direction to close the breaker. The breaker opens until the cam roller comes in contact with the cam surface, the contact motion is then reversed, and the breaker recloses. Operation of the normal trip coil releases a trip-free toggle opening the breaker without a high-speed reclosure. As in the case of the earlier mechanisms, these new mechanisms permit breaker adjustment to reclose contacts in 18 cycles after the trip coil is energized and to do so with a considerably lessened strain.

Two views of this motor mechanism are shown in figures 2 and 3, and a view of the mechanism installed on a standard 138-kv oil circuit breaker in figure 4. The latter illustration is particularly striking when compared with a corresponding illustration of the original mechanism shown previously.

Ultrahigh-Speed Reclosing Installations on 132-Kv Lines of the Central System of the American Gas and Electric Company

The first 132-kv line on which ultrahigh-speed reclosing was installed, was the 59.2-mile line between the Fort Wayne (Ind.) station of the Indiana and

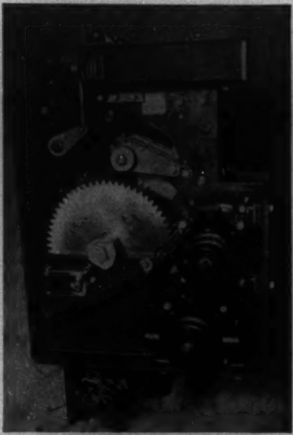


Figure 3. Side view of new ultrahigh-speed reclosing mechanism

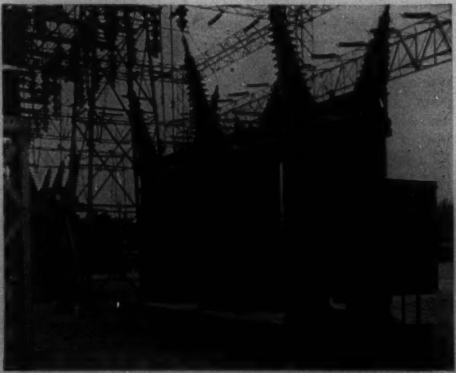


Figure 4. A 132-kv installation of the new ultrahigh-speed-reclosing breaker

Michigan Electric Company and the Deer Creek (Marion, Ind.) station of the Indiana General Service Company. This was placed in operation on May 17, 1936. Figure 5 shows a diagrammatic arrangement of the transmission lines in the area. It will be seen that these include a number of connecting lines comprising a loop circuit radiating from the Fort Wayne station and that they supply not only the Deer Creek station but also the Delaware station of the same company at Muncie, Ind. Although there is an interconnection at Kokomo, it is not of sufficient capacity to supply the entire load of the Indiana General Service Company when separated from the Fort Wayne station. Consequently the load here represents the general condition of a stub load fed from an interconnected system either by a single line or by a double-circuit line on a single-tower line. The solution for maintaining service continuity to this load was, as previously explained, felt to be the application of ultrahigh-speed reclosing, as a necessary part of which one-cycle carrier-current relaying was included. Behind all this was the idea that in case of simultaneous trouble occurring on the two circuits of the single tower line between Fort Wayne and Deer Creek, service restoration on the Fort Wayne-Deer Creek line would be made fast enough to avoid the normal consequences of a double circuit tripout.

The two ultrahigh-speed reclosing breakers used on this line were of the first design employing spring-operated mechanisms. The breakers were adjusted to give an over-all time of 20 cycles from the energization of the trip coil to the time the line was re-energized and that meant a dead time of approximately 12 cycles. The one-cycle carrier relay system gave an actual relay operating time of slightly less than one cycle.

The first operating results previously described and on which further data will be given in this paper were so successful that the same principle was applied on additional line sections. The sections chosen for equipping with ultrahigh-speed reclosing were three sections of a 350-mile double-circuit tie line between the Philo station of The Ohio Power Company, the Twin Branch station of the Indiana and Michigan Electric Company, and the Michigan City station of the Northern Indiana Public Service Company. Figure 6 shows diagrammatically these lines with various sectionalizing stations, generating capacities, and the synchronous condenser capacities installed at the various points. These three stations in turn tie in with very extensive 132-kv net-

Table I. Summary of Actual Operations of 132-Kv Ultrahigh-Speed-Reclosing Oil Circuit Breakers

				Fault						Source Terminal						Load Terminal					
Number	Date	Time	Line Section	Type	Single or Double Line	Cause	Fault Arc Restruck	System or Load Affected	Line De-energized Time (Cycles)	Primary Amperes	Relay Time (Cycles)	Oil-Circuit-Breaker Clearing Time (Cycles)	Oil-Circuit-Breaker Reclosing Time (Cycles)	Total Time (Cycles)	Oil-Circuit-Breaker Retripped	Primary Amperes	Relay Time (Cycles)	Oil-Circuit-Breaker Clearing Time (Cycles)	Oil-Circuit-Breaker Reclosing Time (Cycles)	Total Time (Cycles)	Oil-Circuit-Breaker Retripped
1	6/ 6/36	8:31 p.m.	Fort Wayne-Deer Creek	Phase 3 to ground	Single	Lightning	Yes	No	16.5	300	1.0	6.5	19	20	Yes	1,500	1.0	6.5	21	22	Yes
2	6/17/36	5:31 p.m.		Phase 3 to ground	Single	Lightning	No	No	13	281	1.0	6.5	18	19	No	1,552	1.0	6.0	22	23	No
3	7/23/36	6:02 p.m.		Phase 3 to ground	Single	Lightning	No	No	13	1,170	1.0	6.5	20	21	No	647	1.0	8.0	22	23	No
4	8/28/36	8:59 a.m.		Phase 3 to ground	Single	Lightning	No	No	12.5	563	1.0	6.5	20	21	No	1,165	1.0	6.5	22	23	No
5	5/26/37	3:41 p.m.		Phase 3 to ground	Single	Lightning	No	No	13	937	1.0	7.0	20	21	No	1,140	1.0	6.5	21	22	No
6	6/ 5/37	2:15 p.m.		Phase 1 to ground	Single	Lightning	No	No	12	300	1.0	6.5	20	21	No	1,725	1.0	6.5	21	22	No
7	6/24/37	7:17 a.m.		Phase 3 to ground	Single	Lightning	No	No	13	1,500	1.0	6.0	20	21	No	690	1.0	7.5	21	22	No
8	6/24/37	8:42 a.m.		Phase 3 to ground	Single	Lightning	Yes	No	14	1,125	1.0	6.5	20	21	Yes	863	1.0	7.0	21	22	Yes
9	7/ 3/37	2:30 a.m.		Phase 1 to ground	Single	Lightning	No	No	14	1,690	1.0	7.0	20	21	No	700	1.0	6.5	21	22	No
10	2/19/38	9:31 p.m.	South Bend-New Carlisle	Phase 3 to ground	Single	Sleet	No	No			1.0		18	19	No		1.0		18	19	No
11	5/20/38	3:17 p.m.	Fort Wayne-Deer Creek	Phase 3 to ground	Single	Lightning	No	No	12	1,000	1.0	6.5	20	21	No	1,050	1.0	6.0	20	21	No
12	5/20/38	7:15 p.m.		Phase 3 to ground	Single	Lightning	No	No	10	380	1.0	7.0	20	21	No	1,670	1.0	6.0	20	21	No
13	7/25/38	11:06 p.m.		Phase 3 to ground	Single	Lightning	No	No	15	2,000	1.0	7.0	23	24	No	645	1.0	8.5	23	24	No
14	8/ 5/38	4:51 p.m.	No. 2 Twin Branch–Fort Wayne	Phase 3 to ground	Single	Lightning	No	No			1.0		18	19	No		1.0		18	10	No
15	8/10/38	8:26 p.m.		Phase 3 to ground	Double	Lightning	No	No			1.0		18	19	No		1.0		18	19	No

works totaling some 4,000,000 kw of generating capacity. The flow of power over this tie line on certain sections reaches above 100,000 kw at some times and for this reason it is obviously very important that the continuity of the line should not be interrupted, if at all possible, even in case of simultaneous trouble occurring on parallel lines on the same tower line. Hence it was only natural that with the promising results obtained on the Fort Wayne-Deer Creek line, the solution of ultrahigh-speed reclosing as a means to insuring continuity be tried here.

The 17-mile line between the South Bend and New Carlisle substations was equipped with ultrahigh-speed reclosing equipment and placed in operation on January 29, 1938. The 65.4-mile double-circuit lines between the Twin Branch generating station and Fort Wayne station were equipped with ultrahigh-speed reclosing equipments a little later and the equipments placed in service on July 25, 1938, on one line and on August 31, 1938, on the second line.

The six ultrahigh-speed reclosing breakers used on these three line sections were of the latest design, employing motor-operated reclosing mechanisms of the type shown in figures 2 and 3. All of these circuit breakers were adjusted to give an over-all time of 18 cycles from the energization of the trip coil and that meant a dead time of approximately 10 cycles. The one-cycle carrier-current relay system again gave the usual relay operating time of somewhat less than one cycle.

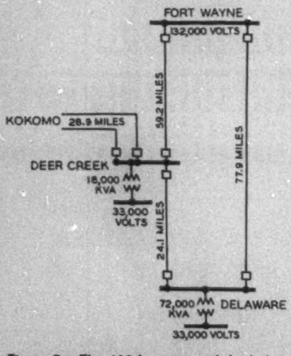


Figure 5. The 132-kv system of the Indiana and Michigan Electric Company radiating from Fort Wayne and supplying Deer Creek and Delaware stations of the Indiana General Service Company

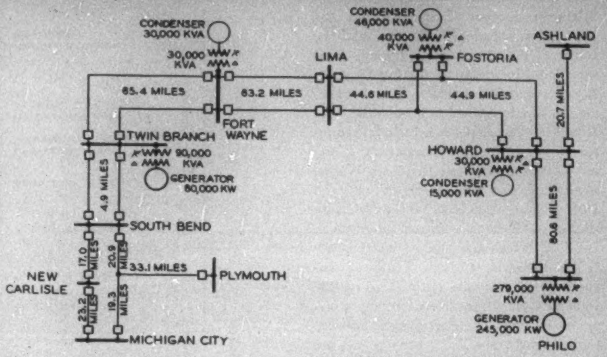


Figure 6. The 132-kv double-circuit tie line of The Ohio Power Company, Indiana and Michigan Electric Company, and Northern Indiana Public Service Company

Operating Experience

With the installation of ultrarapid reclosing equipment on the three line sections described above, there were operating during a portion of 1938 a total of eight 132-kv breakers so equipped and serving four line sections. Since their installation there has been a total of 15 operations on the four line sections. A summary of these operations, all of which except one due to sleet have been traced to lightning, giving the time, type of fault, total time of de-energization, and details with regard to fault current and breaker operation, is given in table I. It will be seen that in all cases flashovers occurred between a phase wire and ground, 12 of the flashovers being between phase 3 which is the top conductor and ground, one between phase 3 which is the middle conductor and ground and two between phase one which is the bottom conductor and ground. In 13 of the 15 cases the breakers on both ends of the line tripped and reclosed without the arc restriking and without any of the normal deleterious effects of a feeder outage being felt in any case. This point, however, needs further elaboration and this will be done below.

In two of the 15 cases the breakers failed to stay in after the first initial ultrarapid reclosure. At least one of these cases analysis shows to be due to multiple lightning stroke and it is quite likely that the other failed to stay in for the same reason. Although in cases 2–7 inclusive and in cases 9, 10, 11, 12, and 13, no normal deleterious effects due to breaker outage and line de-energization were observed, it will be noted that in each of those cases only single line faults occurred. Hence no full test of the efficacy of the steps taken and the equipment installed was obtained in any of these situations. It is, however, interesting that in the case of the Fort Wayne-Deer Creek line where prior to the installation of a one-cycle relaying system, plus the ultrarapid reclosing setup, approximately 25 per cent of lightning flashovers involved both circuits, in more than two years that have elapsed since the installation of the ultrarapid equipment, not a single double-circuit flashover occurred although no other steps of any kind were taken on the line. Whether that is due to chance or whether the reason is to be found in the speeding up of the relaying and breaker action just the necessary amount to prevent involvement of the second circuit by the first to flashover, is something on which additional data will have to be obtained. But the two striking operations that put to at least partially complete test the principles attempted to be developed in this method of operation of high-voltage lines, were obtained in cases 14 and 15, and these deserve more full discussion.

In case 14, the system setup previous to this operation was a case of a single circuit tie between Twin Branch and Fort Wayne stations and a long weak tie line between the Fort Wayne and Plymouth stations. Referring to figure 6, the Twin Branch oil circuit breaker on one of the lines at Fort Wayne station was open due to oil-circuit-breaker revamping to ultrahigh-speed reclosing, and the breaker on the other end of the line at Twin Branch station was closed supplying a tap-off load. A 205-mile tie line between the Fort Wayne station and the Plymouth station by the way of Marion, Kokomo, Lafayette, Oakdale, and Monticello stations was closed. A lightning flashover between phase 3 conductor and ground occurred on the tie line between Twin Branch and Fort Wayne stations, causing the breakers at both ends of the line sections to trip from carrier-current relays and to reclose immediately without restriking without the loss of any load or system disturbance. The speed of operation was sufficiently fast to prevent the opening up of the weak tie line between Fort Wayne and Plymouth stations, which invariably occurred when Twin Branch station was separated from Fort Wayne station before the installation of high-speed-reclosing circuit breakers on these lines.

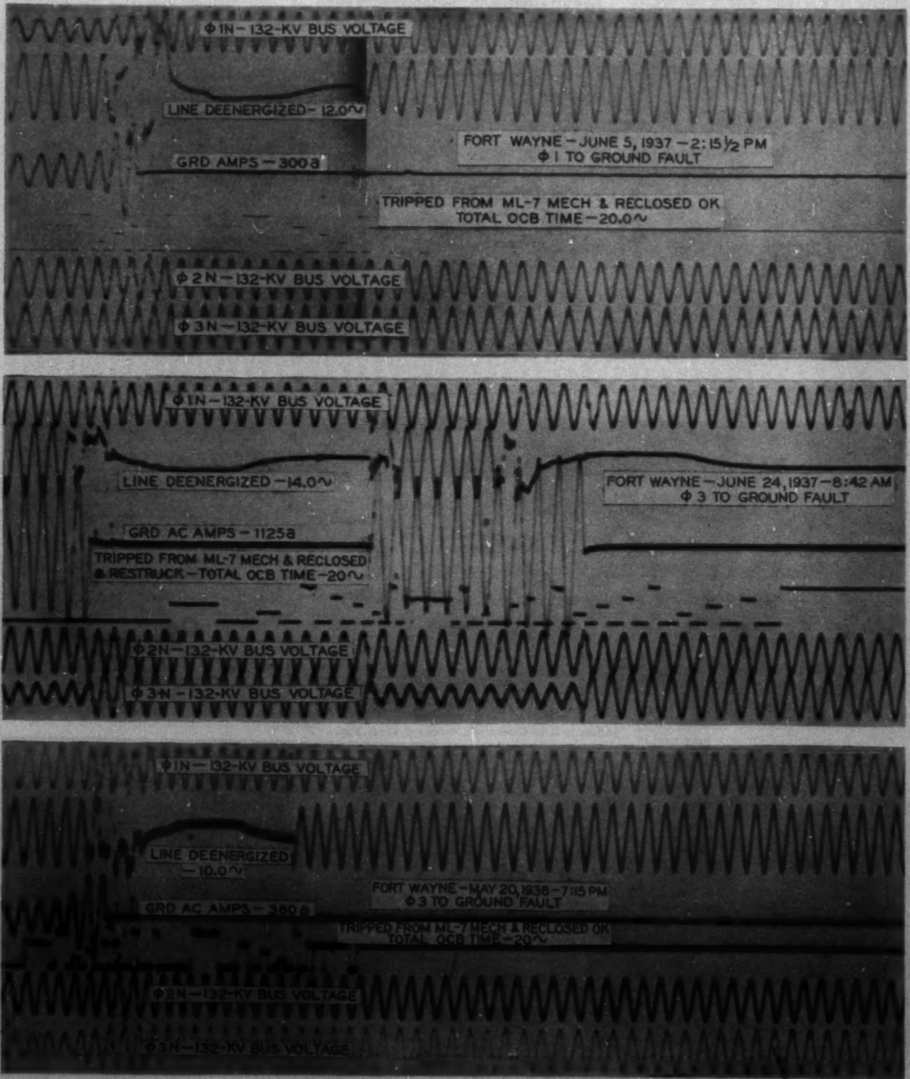
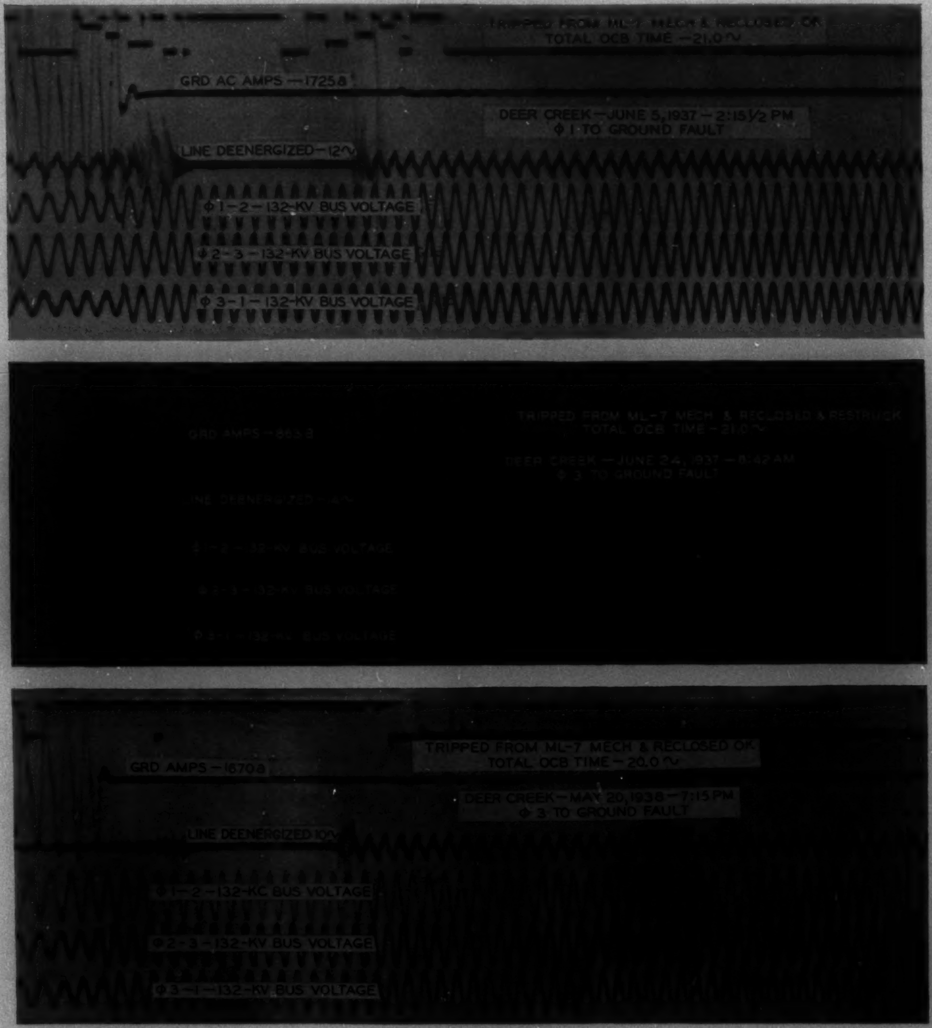


Figure 7. Oscillograms of actual operations on Fort Wayne-Deer Creek line

In case 15, the system setup was normal before this operation in that both lines between Twin Branch and Fort Wayne were in service as well as the weak tie line between Fort Wayne and Plymouth being closed. During a lightning storm simultaneous trouble occurred on both Twin Branch-Fort Wayne lines, causing one of the lines to trip at both terminals from carrier-current relays and to reclose immediately without the arc restriking. On the other line installation of high-speed-reclosing breakers was not as yet completed, and both terminals of this line tripped from instantaneous overcurrent relays since carrier-current relaying was not in service at the time. In this case no loss of load or system disturbance was experienced, and, in addition, the weak tie line between Fort Wayne and Plymouth stations did not open up.

The fact that in similar situations as those that occurred in cases 14 and 15 the system invariably pulled apart gives every reason to believe that the speeding up of the reclosing process can in similar situations be made to give the very desired result of having the systems opened and yet reclosed before either loss of voltage is felt on any part of the system or before the systems drift apart sufficiently to make necessary the introduction of considerable delay until they can be resynchronized. Obviously further expe-

Figure 7 (continued). Oscillograms of actual operations on Fort Wayne-Deer Creek line



rience is necessary in similar situations while carrying loads more nearly within the stability limits of the line. But with the installation of additional equipments it is hoped to be able to present information on the performance under such conditions.

The oscillographic records of the performance of the systems under these conditions are extremely illuminating. In figure 7 are shown three sets of oscillographic records showing system performance in cases 6, 8, and 12. Referring to the record of case 6 it will be noticed that a short circuit occurred close to Marion on phase 1 and that the line remained de-energized for a period of approximately 12 cycles and reclosed without any further disturbance.

The oscillogram of case 8 shows the line voltage on the third trace from the top of the record taken at Deer Creek. This is obtained from a bushing potential device and it will be noticed that at least three cycles before the line was re-energized, potential of possibly three times normal appeared on the line, eventually dying out. The inference is very strong that a lightning discharge took place to the line and that the effect of that was to cause the line to flashover dynamically when it was re-energized some two cycles after the discharge itself had apparently disappeared. The appearance of the same voltage is shown clearly also on the record taken at Fort Wayne, except to a lesser extent. A possible explanation of that is that the voltage at Fort Wayne is measured by a regular instrument-type potential transformer.

The record of case 12 was obtained on May 20, 1938, and shows a successful reclosure of the Fort Wayne-Marion line. It will be noticed in this case that the fault was very close to Deer Creek and after a line de-energization of ten cycles, reclosure was entirely successful.

New Installations

The 80.6-mile double-circuit 132-kv lines from the Philo Generating station to the Howard substation (see figure 6) are both at present being equipped with ultrahigh-speed-reclosing circuit breakers in conjunction with one-cycle carrier relaying and it is expected that these will be placed in operation the early part of next year. This is another step in making this 350-mile tie line immune to interruption in continuity for simultaneous trouble occurring on two lines on the same tower line.

Plans are under way to install ultrahigh-speed-reclosing circuit breakers on the 77.9-mile 132-kv line between the Fort Wayne station of the Indiana and Michigan Electric Company and the Delaware substation of the Indiana General Service Company (see figure 5). It is expected that these installations will be put in operation before the next lightning season. The aim in this case is to install ultrahigh-speed-reclosing circuit breakers on both of the 132-kv supply circuits radiating out from the Fort Wayne station to insure uninterrupted service to this important load in case of simultaneous trouble occurring on both of these lines, one of which it is hoped will remain closed after the first reclosure.

A number of other points on the American Gas and Electric system still remain where principal source of supply comes in either over a single-circuit line or over a double-circuit line running on the same right of way without some loop backup. In all of these cases it is expected over the next year to install ultrarapid reclosing as fast as the breaker and relaying problems in connection therewith can be properly worked out and taken care of.

Conclusions

The results obtained so far, it appears to the authors, definitely warrant the following conclusions:

1. On high-voltage overhead lines outages caused by lightning can be materially reduced by ultrarapid reclosing. The originally[1] expected figure of 75 per cent seems conservative in the light of the additional experience obtained since that time.

2. Apparently two-circuit flashover, on double-circuit transmission lines properly equipped with ground wire, when the two ends are equipped with ultrarapid-reclosing breakers is materially reduced. It does not appear that the ultrarapid reclosure element can be a major contribution in this regard and it would appear, therefore, that this is in a large measure the result of a speeding up of the relaying and circuit interrupting process. More information on that is needed and it is hoped to gather it over the ensuing years.

3. It appears definitely that not only can service continuity materially be improved by the installation of ultrarapid reclosing on lines feeding isolated areas, but the use of ultrarapid reclosing on tie lines between two major generating systems will result in line flashover having a minimum effect on the continuity of power flow. Apparently even when handling power close to the stability of the line ultrarapid reclosure when properly functioning can be made to bring two systems together without the necessity of a wait for synchronization and without the danger of system drift to a point where reclosure without synchronization produces any deleterious effect or fails to keep the two systems together.

4. The experience with ultrarapid reclosure seems to indicate the need for a complete re-examination of the concept of the switching process on any important high-voltage circuit, consisting of relaying, de-energization, and re-energization of the circuit. If ultrarapid reclosure will accomplish, in a vast majority of cases, the results here indicated, it would appear logical to consider that under all cases the proper cycle of operation is one in which ultrarapid reclosure to the extent of one reclosure ought to become standard practice and that only in exceptional cases ought a period of waiting longer than the absolute minimum required for deionization, be permitted between de-energization and reclosure.

5. The work carried out on high-voltage systems seems to indicate that very much similar results can be obtained on intermediate and low-voltage lines by utilizing the same principle. The exploration of that field is a problem for the future. The authors themselves hope to be able to contribute something to that.

Reference

1. ULTRAHIGH-SPEED RECLOSING OF HIGH-VOLTAGE TRANSMISSION LINES, **Philip Sporn** and **D. C. Prince.** AIEE TRANSACTIONS, volume 56, 1937, pages 81–90.

Discussion

S. B. Crary (General Electric Company, Schenectady, N. Y.): The benefits which have been obtained from quick switching and relaying have been fully demonstrated in practice and by system studies and stability analyses. More recently immediate reclosure of standard circuit breakers has been applied with pronounced success to feeder circuits and to a limited extent to tie lines. Now Messrs. Sporn and Muller present operating data showing the improvements which they have obtained by combining quick switching with rapid reclosure by means of special, fast, breaker mechanisms and relaying. Those of us who are engaged in making system studies are impressed with the benefits which may be derived from quick switching and quick reclosing and the possibilities it opens up for improving the reliability of service. Undoubtedly, in almost every major system, there are circuit-breaker locations and system conditions for which quick switching and rapid reclosure would be or are of material benefit in improving service. Some circuit-breaker locations and system conditions make quick clearing and reclosing more desirable and favorable than others. These locations and conditions are generally recognized and can be determined quite accurately by a system analysis.

A system analysis based on operating records of the types of faults to be expected along with information similar to that present in the paper, can be used to predict the expected improvement in system performance. There are now generally available a-c network analyzers and developed procedures for making such studies. In recent years a better understanding has been obtained of the transient performance of machines and systems undergoing system disturbances and out of step conditions, both from an analytical and an operating point of view. No small part of this new knowledge has been contributed by the automatic oscillographs. As an aid in determining the electromechanical oscillations to which rotating equipment is subjected during out of step and pulling into step conditions, the differential analyzer has also been put into use. All of these methods of analysis have contributed to a better understanding of system and machine performance and have made it possible to predict more accurately their behavior. This knowledge can be used to advantage in the rational application of quick reclosure to power systems.

With simultaneous circuit-breaker tripping by means of carrier-current relaying and an over-all time of 18 cycles from energization of the trip coil to breaker reclosure an accomplished fact, it becomes evident that such equipment may be more generally used to prevent loss of synchronism between two systems for even more severe conditions than that reported in the paper by Messrs. Sporn and Muller. It should be recognized, however, that there do exist limitations as to how much power may be carried through a disturbance with a successful reclosure for a given set of conditions. The more important factors are the synchronizing strength of the electrical tie, the effective system inertias, the fault location, number of phases involved, fault duration, and reclosure time. However, the effect of these factors may be evaluated and the power limitations predetermined with fair accuracy by analysis.

A factor of considerable importance favoring the reclosing principle which is becoming more fully recognized is the ability of systems to pull together even after being closed-in out-of-phase or definitely out of step. The conditions and factors which allow for this resynchronization are determined to an appreciable extent by the automatic control devices, voltage regulators, and governors, which are attempting to hold the voltage and speed of the individual parts of the system. There have been several cases where this ability of systems to regain synchronism has been fully demonstrated. An important factor in such resynchronization is that the relaying should not be sensitive or operate during the out of step or pulling into step process. Such a consideration may tend to influence the relaying philosophy of a system which intends at some future time to take full advantage of quick reclosure. This constitutes an important reason why it is advisable to give immediate careful consideration to the reclosure problem. The factors which allow systems or parts of systems to resynchronize are also amenable to analysis. Since system performance can be studied evaluating the effect of the factors influencing system operation following reclosure, it is believed that in the future more consideration and study will be given to this problem in a similar manner as was done in the past, in studying the effect of quick clearing of faults as a factor in system and machine stability.

It has been suggested in the case of two parallel circuits which are equipped with quick switching and reclosing that a control scheme be used which will allow for quick clearing and reclosing of the faulted circuit, if only one is involved, when the load to be carried through the disturbance is above the stability limit of one circuit. However, in the case in which the load to be transmitted is below the stability limit with one healthy circuit left in service, reclosure on the faulted circuit is delayed in order to reduce the possibility of reclosing on an uncleared fault at an inopportune time of the system oscillation. Accordingly, in this case it is conceivable that the probability of proper system operation is actually increased by delaying the reclosure. However, if operating near or above the stability limit of one circuit it may be advisable to reclose as quickly as possible. The justification of using this type of control is determined among other factors, by information of the nature which Messrs. Sporn and Muller are accumulating, such as the percentage of faults which clear during the breaker reclosure time, the number of phases and circuits involved in the fault, etc. Their results are of considerable value and should encourage the consideration and study of a more general use of rapid reclosure.

E. E. George (Tennessee Electric Power Company, Chattanooga): In the first part of their paper Messrs. Sporn and Muller use one argument which might bear considerable emphasis. They state that the electrical industry ought not to wait for a complete and precise evaluation of all factors involved before utilizing high-speed reclosing. Most of the transmission companies in the Southeast would agree that ultrahigh-speed reclosing is desirable on all high-voltage lines; nevertheless they have not waited for high-speed-closing breakers. So-called immediate reclosing was put in use in the Southeast about five years ago and has since been considered standard practice on all transmission and distribution lines since that time. It has now been applied to practically all existing lines.

High-speed reclosing is of much more value today than it was a few years ago. Lines are being built better and there is increased probability of coming back in service "OK" after an interruption. Many years ago when a large percentage of line failures resulted in burn-downs and permanent trouble it was "OK" to do switching on the basis "where there's no hope there's no hurry." With breakers of the closing speed standard until recently, the reclosing time has varied from 75 cycles at 154 kv to 15 cycles at 2,300 volts with the majority of operations between 45 and 25 cycles.

It is now standard practice of The Tennessee Electric Power Company to reclose immediately on *both* ends of tie lines if pilot wire or power carrier protection is available. This is applied regardless of lower-voltage loops, transmission loops through the rest of the system or through interconnecting companies, etc., although it might not be adequate if a generating plant were tied to the system with only one line.

This reclosing is being used at both ends of 110-kv, 44-kv, and 11-kv ties, most of which are short and protected with pilot-wire relays. Wherever the relaying is too slow to permit instantaneous reclosing on both ends it is used on one end with synchronism check or dead bus reclosing on the other, thus restoring the line in a few seconds.

Many of us have talked about faster closing of oil circuit breakers for several years but outside of Mr. Sporn and his associates we have done very little about it. In answering a questionnaire on the subject of reclosing about five years ago our company stated that we would reclose breakers in ten cycles if the equipment were available. We still stand by this opinion and feel that reclosing even faster than Mr. Sporn is using would work out satisfactorily in most cases. Operating experiences have shown that little weight should be given the fear of multiple lightning strokes or reignition of an arc across transmission insulator strings. Multiple lightning strokes are largely confined to certain rare types of lightning storms, but do not seem to occur frequently, at least when we are talking about multiple strokes a few cycles apart rather than a few microseconds apart. In this area our worst lightning occurs in windshift storms during the passage of a cold front, and the lightning is generally accompanied by high winds. This tends to prevent reignition of an arc.

Experience in the southeastern area would indicate that all new transmission lines should be designed to utilize the development discussed by Messrs. Sporn and Muller. However, on existing transmission lines great advantage can be obtained with existing relays and breakers by applying immediate reclosing.

A. J. A. Peterson (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors are to be commended for the confidence with which they have proceeded to equip their important 138-kv transmission lines with high-speed reclosing equipment as described in this paper, and the results described in their paper well justify their work in this direction.

As pointed out in the paper, the practical limit on high-speed reclosure is determined by the time of complete outage required for deionization of the original fault path, which time, of course, increases with the service voltage. This confirms the findings of Griscom and Torok ("Keeping the Line in Service by Rapid Reclosing," *Electric Journal*, May 1933).

Even though the limit on reclosing speed for the circuit breaker is to a large measure determined by this deionization time, faster

Figure 1. Early high-speed motor mechanism

arc interruption will obviously permit faster over-all reclosing time, and therefore, better maintain system stability.

With the fault current interrupted, the next step in restoring service and maintaining stability is to reclose the breaker quickly. The mechanics of a quick reclosing cycle are: first, fast opening of the breaker; second, stopping the opening stroke; and third, closing the breaker. Trip-free action must be provided so that the opening action will not be unnecessarily delayed by the mechanical or magnetic drag of the closing means. We have been working on such a mechanism for several years. Figure 1 of this discussion shows a high-speed circuit-breaker operating mechanism. It consists essentially of two sets of springs, one for closing and the other for tripping. These springs are charged by motor. Drive from the springs to the breaker mechanism is through a "capstan" clutch which gives very quick engagement at any part of the stroke, thus permitting fast closing at any desired point on the opening stroke, as well as trip-free operation at any point on the closing stroke. In reclosing, the closing means is controlled to initiate closing of the breaker before the full open position is reached. The mechanism thus quickly stops and reverses the breaker, and carries it back to its closed position.

A further development of the mechanism is shown in figure 2. This mechanism is a direct motor drive, using the same type of "capstan" or band friction clutch. The high-torque high-speed motor drives a helical band friction clutch through suitable worm gearing. This clutch freely rotates around a drum attached by suitable shaft, crank, and levers to the breaker operating rod. In order to close the breaker, the motor is energized and quickly comes up to speed. At the same time, the friction band is snubbed into action around the breaker drum by a low-energy magnetic face plate. This couples the breaker directly to the motor drive. Trip-free action is obtained by simple de-energizing the snubber, thus releasing the breaker drum from the motor friction band, and permitting the breaker to open freely through its normal accelerating springs. The same design of mechanism for 138-kv breakers is shown in figure 3. Because of its inherent ability to get into action quickly, this mechanism is well adapted to provide high-speed reclosing on a fast-opening breaker.

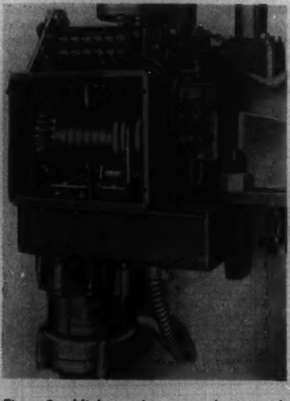


Figure 2. High-speed motor mechanism with "capstan" clutch, front view

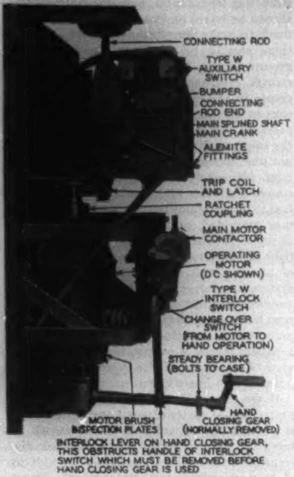

CONNECTING ROD
TYPE W AUXILIARY SWITCH
BUMPER
CONNECTING ROD END
MAIN SPLINED SHAFT
MAIN CRANK
ALEMITE FITTINGS
TRIP COIL AND LATCH
RATCHET COUPLING
MAIN MOTOR CONTACTOR
OPERATING MOTOR (D C SHOWN)
TYPE W INTERLOCK SWITCH
CHANGE OVER SWITCH (FROM MOTOR TO HAND OPERATION)
STEADY BEARING (BOLTS TO CASE)
HAND CLOSING GEAR (NORMALLY REMOVED)
MOTOR BRUSH INSPECTION PLATES
INTERLOCK LEVER ON HAND CLOSING GEAR, THIS OBSTRUCTS HANDLE OF INTERLOCK SWITCH WHICH MUST BE REMOVED BEFORE HAND CLOSING GEAR IS USED

Figure 3. High-speed motor mechanism with "capstan" clutch, for 138-kv oil circuit breaker, side view

D. C. Prince (General Electric Company, Philadelphia, Pa.): Engineers are constantly under pressure to find ways of providing better service at reduced cost. Any improvement in line availability and freedom from interruption is a step in this direction.

Overhead ground wires, improved grounding, additional insulation, Petersen coils, expulsion gaps, duplicate lines, and ultrahigh-speed tripping and reclosing are all means of improving continuity of service. Each of these steps affects continuity of service in a different manner; each has its cost, each must be judged in the last analysis by field experience.

Ultrahigh-speed reclosing is a means toward service improvement which presented originally a good many problems. First, ultrahigh-speed-reclosing means had to be devised; then laboratory and field tests had to be made to determine how fast reclosure would be useful. And then, finally, it was necessary to find how much of the possible theoretical gain might be realized in practice. The authors of this paper are to be congratulated and thanked for furnishing an answer to this last and crucial question.

The improvement in service appears to compare favorably with that obtained by other means. High-speed reclosure is applicable to any type of temporary fault whether phase to ground or phase to phase, and whether from lightning, sleet, or birds. It does not eliminate tripouts, but judging from the paper, does reduce loss of load which is the important element. Since breakers are required in any case, the cost of securing this improved service by high-speed reclosure is very moderate considering the improvement obtained.

It will be very interesting to see to what extent high-speed reclosing can be used as a substitute for other more expensive means of assuring service continuity.

Percy H. Thomas (Federal Power Commission, Atlanta, Ga.): Mr. Sporn and his associates have added another to the long series of fundamental and classic papers, on the problem of the adequate control of the flow of electric energy in heavy power circuits, and in the usual style—brief, to the point, and adequate.

A look ahead as to the ultimate critical factors in this most important aspect of the control of the flow of electric energy may be of interest.

What can be done to increase the length of the time of interruption that may be permitted without loss of synchronism in the system? With the complexity and infinite variety of conditions met in utility power circuits, no general particular method of extending this time seems probable. On the other hand, if and when the use of reclosing breakers is extended and the holding of synchronism becomes critical, no doubt a study of individual situations will show effective means to secure a material improvement. With the present available methods of recording transient phenomena in power circuits and the means for mathematical analysis, such a study offers little difficulty.

What can be done to shorten the time required for the extinguishment of the arc when the operation is to interrupt a flashover?

As stated in the paper, the prompt interruption of the current after the initial breakdown is of the greatest importance. The amount of matter heated and the accumulated energy generated in the arc might increase as the cube, or higher, with a proportionally rising current. Since the opening oil breaker introduces an important resistance in the line long before the current is interrupted, the saving in the accumulation of heat in the flashover arc will be very greatly reduced by quicker operations. That portion of the duration of the arc in which the current is a maximum would be materially shortened. But the saving is double: first, the saving of time in the opening operation; second, the lessening of the interval of waiting, with the current interrupted, for the arc to die out.

That this rapidity of action is important and very potent, is shown first by the well-known experiments of Nicholson on quick-acting arc switches and fuses, and, second, by the effectiveness of the low-voltage high-speed d-c breaker.

Such a phenomenon as the multiple lightning flash should presumably require a different treatment to avoid handicapping all the opening operations by a lengthy waiting period to meet the occasional special case.

Can anything be gained in opening the circuit by basing the action of the opening relay on the rate of rise of the flashover current? This "rate of rise" will be greatest at the start and will of course be at a maximum only when the total impedance of the arc circuit is small; that is, when the arc current is potentially very large. If the secondary of a line current transformer is connected to a relay of high resistance, preventing a saturating flow of current in the transformer, the relay would be subjected to a voltage proportional to the rate of rise of the arc current. This should represent some gain in relay action.

What advantages may be hoped for from changes in the mechanical construction of the breaker? No doubt with the excellent performance so far secured, evolution for the immediate future and for the immediate expansion of utility use should continue with substantially the same model. However, in seeking the ultimate best layout, other radically different forms should be considered, as in the end somebody will get a better type if the possibility exists. It is well recognized that at times less advantageous types of apparatus have been long used in practice in the electric art where better ones were potentially available.

In these breakers, the interests of size and cost and upkeep put a very great premium on light moving parts. Designs with possibly five to ten per cent of the mass of those here used would have a great advantage in these matters of cost and size, as well as speed. A radial blade carried by a rotating shaft, as already used in some designs, offers a tempting field for the designer. The very speed of action attainable might eliminate the necessity of some of the present arc-suppressing features. It may well be that a sufficiently rapid extension of the rupturing arc in the breaker through oil, under an initial moderate pressure, might have a miraculously increased effectiveness.

Is the growing aggregate capacity of generating stations and the necessity of increasing rupturing capacity likely to develop into a limitation in the use of reclosing breakers? It would be a natural inference from the reports of tests and construction difficulties in these "Sporn" papers that the economic rupturing capacity limit was very likely being rapidly approached in this type of construction.

There are at least two avenues of escape to be considered: first, the beneficial effects of more rapidly moving parts in breakers; second, the adoption in the layout of large electric power systems to cut the concentration of too great short-circuit power on any one bus or connection point. This can be accomplished, as is well known, oftentimes by paralleling large generators only through the distribution systems. Where there are several large generating stations on a network, the loose coupling of units can be accomplished, at least in a new system, with very little added cost. In such a case a great limitation of the present demands for flexibility in a major power station would be a minor handicap in operation, though requiring some sacrifice of habits of thought and a different point of view on the part of the station operator.

The writer has long advocated this approach to the solution of the threat made by the concentration of generating capacity.

In closing this discussion, the writer desires to point out what seems to him the natural conclusion from the availability of the reclosing breaker, that is, that, assuming that a satisfactory method of handing flashovers has been found, new line construction should be based on this fact and no effort be made to make lines flashover-proof. Reductions should be made in the heights of ground wires, in the length of insulator strings, clearances, etc. When the vast increase in the expense of overhead construction in the last few years, and the present pressure for lowered cost are remembered, the opportunity should be welcomed. It is not unreasonable to hope that ground wires may ultimately be largely omitted. Of course engineers and operators will be very loath to build lines with less insulation than now provided, and it will be agreed that changes should come step by step in the light of resulting experience, but, in the view of the writer it is the duty of our leading system managers, in appropriate cases, to consider carefully and initiate this policy. It may be pointed out that a low-insulated line protected with reclosing breakers may have a higher factor of safety, from the point of view of operation of the system, than a superinsulated line without such protection.

If we may add to the reclosing breaker protection, a system layout such that there is always the capacity in the network to serve the load with any particular link disconnected for a while, the result is a system of reserve, which provides against almost any form of interruption, whether lightning, mechanical failure, or operative error, and a system which does not require any supertypes of construction. One interruption a month on any unit in such a system would presumably not disturb operation and would be good practice.

While comments and suggestions of this sort may be sound and of a great potential value, the credit for any benefits resulting must go to those who have the foresight, the courage, the stamina, and the facilities for making the initial application.

V. M. Marquis (American Gas and Electric Service Corporation, New York, N. Y.): One reclosure which has not been discussed by the authors and which gave an excellent check on the ability to reclose between two large systems without losing synchronism when transferring heavy load occurred on November 16, 1938, on the South Bend-New Carlisle 132-kv line. The location of this line and its relation to the other parts on the system is shown in figure 6 of the authors' paper.

A fault on the Plymouth tap caused a trip-out of the South Bend-Plymouth-Michigan City line when about 80,000 kw was being delivered east from Michigan City, 50,000 kw of which was delivered to South Bend and 30,000 kw into the Plymouth substation. The tripping out of this line threw the entire 80,000 kilowatts on the Michigan City-New Carlisle-South Bend circuit and, immediately following, the South Bend-New Carlisle line tripped and reclosed successfully while carrying the load of 80,000 kw. Figure 4 of this discussion shows a graphic record of power flow over the line at New Carlisle substation; the load change due to the opening of the Michigan City-Plymouth-South Bend circuit and the reclosure on the South Bend New Carlisle circuit is shown at *A*. In figure 5 is shown a graphic record of the 132-kv bus voltage at South Bend substation. This meter is equipped with a high-speed trip attachment, but the surge was not sufficient to operate it; however, the record indicates that the fault on the Michigan City-Plymouth-South Bend line caused a voltage dip of some six volts and the reclosure a dip of only about two volts.

In this particular instance, the operators at Michigan City did not know that the South Bend-New Carlisle line had tripped out until some time later when the operators at South Bend and Michigan City were interchanging data on relay targets. This is no reflection on the alertness of the operators but rather, as I see it, a compliment to the ultrahigh-speed reclosing equipment.

Previous calculations had incidated that there would be no difficulty in reclosing this circuit when carrying a load of 80,000 kw over it and this operation bore this out. This operation, it is believed, was an excellent demonstration of the possibilities of ultrahigh-speed reclosing on important high-voltage ties.

With reference to the high-speed reclosing on the Twin Branch-Fort Wayne circuits, it is of interest to note that a load is tapped off one of these circuits midway between Twin Branch and Fort Wayne. During the reclosures that have occurred on this line, the loads fed by this tap have not been disturbed.

The authors in conclusion 3, in discussing improvement to service due to high-speed reclosing, point out that it is apparently possible to reclose even when operating near the stability limit of the line. It is perhaps pertinent to point out that the time available for reclosing of a tie line between

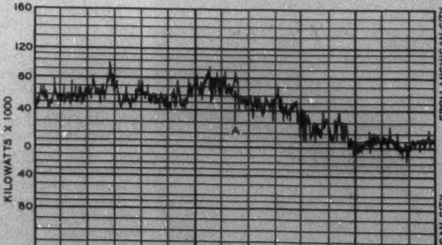


Figure 4. Power interchange on South Bend-Michigan City tie recorded at New Carlisle substation

Reclosure at *A*

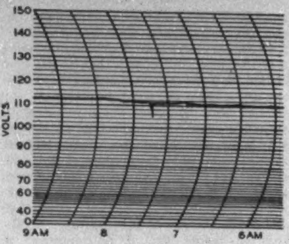


Figure 5. The 132-kv bus voltage at South Bend substation

Voltage dip not sufficient to operate high-speed trip on voltmeter

two systems without losing synchronism is dependent upon several factors, one of which is the relative inertias of the two systems. Whereas as much as 30 cycles might be available when reclosing between two large systems, calculations indicate that something under ten cycles would be available when reclosing, for example, between a hydro plant and a large steam system, if reclosure is to be made without losing synchronism. However, there has been some experience in reclosing and holding the systems together even when they are out of phase. Further experience may indicate that there will be no particular difficulty in such cases even with the present speeds available for reclosing.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): It is interesting to compare the data on multiple strokes with the performance figures obtained for successful automatic reclosure operation reported by Messrs. Sporn and Muller. Figure 6 of this discussion is taken from a paper entitled "Multiple Lightning Strokes—II" (K. B. McEachron, AIEE TRANSACTIONS, volume 57, 1938, page 510) and shows the operations of expulsion protector tubes as measured oscillographically in those cases where two or more successive operations were involved. The record shows tube operations on the 132-kv Roanoke-Glenlyn and Roanoke-Danville lines of the American Gas and Electric Company. Table I of the paper referred to shows a total of 184 discharges, which operated protective tubes during the four-year period of study beginning with 1934.

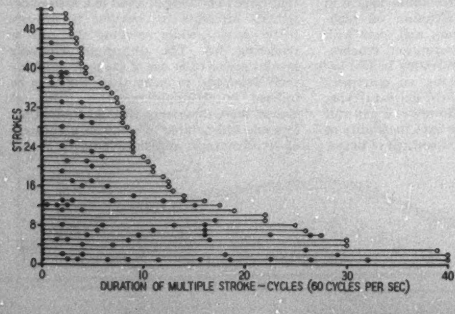


Figure 6

Of these 184 discharges, 52 were multiple, and from figure 6 of this discussion 10 are seen to involve a longer time than 20 cycles, or a little over five per cent of the total strokes which were of sufficient magnitude to cause tube operation, which no doubt also means that sufficient potential was encountered in most cases to have caused an insulator flashover.

If the total time is reduced from 20 cycles to 15 cycles, as an illustration, the number of times in which a single reclosure would not be satisfactory is increased to six per cent. This indicates that the shape of the curve is such as to show that the deionization time becomes controlling rather than the multiple discharges, from the point of view of decreasing reclosing time.

However, I do not believe that the above gives a clear picture of the true situation, because the data which we have available with Boys camera photographs, taken both in Pittsfield and in New York in the Empire State investigation ("Lightning to the Empire State Building," K. B. McEachron, *Journal* of the Franklin Institute, February 1939) since 1934, indicate that an appreciable percentage of the successive discharges of a multiple stroke will be continuing. That is to say, the current will persist for a considerable period of time after the initiating discharge has decreased to a relatively small value. It has been shown, for instance, that currents as great as 250 amperes may persist for as long as 0.4 second.

In the case of data shown in figure 6 of this discussion, the transformer neutrals were grounded, with the result that the direct current of the continuing discharge finds a ready path to ground when interrupted by the expulsion action of the protector tube at the point of inception. With the operation of the circuit breakers, the line is left isolated from ground, if high-voltage switching is used, with the result that the continuing current will hold on as a d-c arc over the faulted insulator string. The occurrence of this type of discharge tends to decrease the number of successful operations to be expected using one reclosure below that which might otherwise have been expected.

Perhaps some indication of the most pessimistic view might be obtained from a consideration of the results of strokes to the Empire State Building, in which, out of a total of 67 photographed, 27 had a duration of more than 0.33 second, or 20 cycles. On this basis, 40 per cent of the breaker operations would not have been successful. However, these results are undoubtedly influenced by the fact that many of the strokes began at the building rather than at the cloud, which is the usual case for transmission lines.

I am inclined to the view that the second oscillogram of the authors' figure 7 is a case of this sort, in which a continuing discharge caused the line to be in a faulted condition at the moment the breaker closed.

It seems to me that, for the present, until more accurate data are available, with a dead time as long as 14 cycles and a total time of 20 cycles, if a fault exists at the time of reclosing, it will be as a rule the result of a continuing discharge. If it occurs a cycle or more after reclosing, then it would appear to be either a multiple discharge or another stroke.

In lieu of any more accurate information, I would suggest a figure of 20 per cent as representing about the number of unsuccessful operations to be expected on the line with which Messrs. Sporn and Muller have experimented, as a result of multiple or continuing strokes.

Although the protector tube has its limitations, it does perform successfully on multiple strokes with long times included between the first and last discharge, and it ought to be free from the effects of continuing strokes on grounded–neutral systems.

It will be of interest to engineers to learn of the further experience which Messrs. Sporn and Muller will secure with automatic reclosing, and I hope that they will continue to secure oscillographic data which will help materially in determining the cause of unsuccessful reclosure.

S. B. Griscom (nonmember, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors have presented most interesting data on a power system operating procedure which is probably destined to find an extensive future use. While calculations can be made to determine whether two parts of a system will be held together after a high-speed reclosure, they do not take the place of the assurance obtained by actual operation and the proof that some obscure factor has not been omitted from consideration.

In reading this paper, I looked over the illustrations before proceeding to the text, and after examining the Fort Wayne oscillograms of the case 8, June 24, 1937, fault, I concluded that this was an example of a restrike due to insufficient deionization time. This was based merely on the fact that in both the initial fault and the subsequent reclosure, the fault was from phase 3 to ground, as evidenced by the lowest voltage being on phase 3.

Upon reading the text, it was found that the authors had concluded that the evidence pointed a repetitive lightning stroke. This conclusion was inferred from the simultaneous oscillogram at Deer Creek where a disturbance on the line-voltage trace was noted three cycles before the actual reclosure. The restrike was interpreted as being due to the residual ionization from the lightning stroke persisting during the three intervening cycles before the circuit breaker reclosed.

It may not be possible to establish definitely whether in this particular instance the restrike was caused by residual 60 cycle ionization or by residual ionization from a repetitive lightning stroke during the deenergized period. However, the principle is important because if the former, it will have a bearing on the allowance to be made for de-ionization time, while if the latter, since repetitive strokes are a random phenomena, nothing can be done about it.

Mr. Torok and I collaborated on an article "Keeping the Line in Service by Rapid Reclosure" in the May 1933 *Electric Journal*, and a large number of high-speed movies of 60-cycle arcs were taken in the preparation of data. I have just re-examined some of these to get an idea as to the length of time evidence of the 60-cycle arc remained. It was not uncommon to find that incandescent gases remained as long as 30 cycles after the current had been interrupted. However, as the oscillographic results showed, it was rare for the arc to restrike after 12 cycles, although it was a random occurrence. The evidence is that the flashover path gained dielectric strength because the ionized gas had drifted from the proximity of the electrodes by convection currents or action of wind, rather than because the gases had become sufficiently deionized again to withstand the applied voltage.

Such evidence that I have been able to locate indicates a different action in the case of arc paths due to lightning. Messrs. Brookes, Southgate, and Whitehead in AIEE paper 33–44 made tests indicating that power follow from lightning was affected by the magnitude of the 60-cycle voltage at the instant of the surge current. In tests on "De-ion" protectors, it is found that surges taking place near voltage zero are much less likely to result in power follow. This is a somewhat different circumstance, of course, since the discharge is confined. However, both examples seem to indicate that the arc space from lightning strokes recovers dielectric strength much more rapidly than that from 60-cycle arcs being measured possibly in hundreds of microseconds rather than in thousands.

Although the Deer Creek oscillogram for case 8 was not very distinct, there appears to be another surge on the "line de-energized" trace, about four cycles later than the cessation of the reclosure ground current. There also seems to be slight evidence of a counterpart on the Fort Wayne record, but this is only about two cycles later than cessation of the ground current. The duration of the ground currents was not the same at both stations so this may account for the difference. These disturbances are similar to those attributed to the repetitive stroke, which if that theory is correct, may indicate still a third stroke.

Philip Sporn and Charles A. Muller: Mr. Crary's discussion gives some idea of the general groundwork which must be performed to predict results to be expected from ultrahigh-speed reclosure, a very necessary step in justifying it economically. It is interesting to note that in the case of parallel lines equipped with ultrarapid reclosure it may be desirable to delay reclosure for a fault on one line if the total load is below the stability limit of a single line. This condition was considered in the case of the Twin Branch-Fort Wayne lines, but because of the additional complications in control which are involved it was decided to wait until operating experience should more clearly indicate its desirability.

Mr. Thomas has made some stimulating comments as to the possible future lines of investigation in improving the design and effectiveness of ultrahigh-speed-reclosing breaker applications. It is hoped that breakers will soon be available which will considerably reduce the amount of time required to extinguish the arc, and that this will, in turn, allow a reduction in the length of time the line must be de-energized, as Mr. Thomas suggests. This possibility was referred to in Messrs. Sporn and Prince's AIEE first paper on "Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines," in which tests were cited that indicated that by reducing the arcing time from eight cycles to two cycles the time required for the line to be de-energized was reduced by about 25 per cent. In regard to Mr. Thomas' suggestion of employing a "rate-of-current-rise" relay as a possible means of decreasing somewhat the relay time required the authors believe that the present relay time of one cycle could not be materially reduced, and, since this is only a small portion of the total arcing time, any small gains in this time would be of minor importance in the over-all reclosing cycle.

Mr. Marquis has described an additional reclosure to those listed in the paper, which probably represents the most severe operating condition so far encountered. The fact that this reclosure was successful and it had been indicated from previous calculations that it would be, gives added confidence in the accuracy of the preliminary analysis as well as concrete evidence of the value of the equipment.

Mr. George brings out the point that the Tennessee Electric Power Company has been employing immediate reclosing as standard practice on all transmission distribution lines for the past five years, and that his company now recloses immediately both ends of tie lines equipped with carrier current or pilot wire relay systems. This is excellent operating practice but it needs to be emphasized that immediate reclosure at best is from two or three times longer in time than ultrarapid reclosure on high-voltage transmission lines, and that with this longer time of interruption, synchronism would probably invariably be lost between systems not having an extremely large amount of inertia if the line is carrying any appreciable load. However, it can still be of value if the systems have the ability to pull in step even though closed out of phase, as pointed out in Messrs. Crary's and Marquis' discussions.

From Mr. Griscom's comments on figure 8 of the paper, it appears that he has concluded as a result of laboratory tests that the cases where the 60-cycle power arc will restrike after 12 cycles would probably be extremely rare. It is especially interesting that he apparently believes the arc will not restrike after 12 cycles because of the probability that the ionized gases will have been swept out of the path along which the arc would probably be established rather than due to the absence of deionization. As Mr. Griscom points out, it is important to know whether the reestablishment of the arc is caused by a continuation of the 60-cycle ionization or by a multiple lightning stroke, or, as Mr. McEachron also suggests, by the possibility of a continuous lightning stroke. Incidentally, Mr. McEachron's discussion brings up a most important point in connection with the entire problem of lightning protective apparatus and the effect on it of the continuous lightning stroke. It is obvious that a great deal of our thinking as regards the requirements of lightning protective equipment will have to be considerably modified if such equipment is actually being subjected to continuous flow of current from lightning strokes of from 0.3 to 0.4 second.

It will be interesting to observe the actual operating data as it is gathered over the years and determine how the percentage of unsuccessful operations actually obtained compares with the 20 per cent which Mr. McEachron suggests as being probable. As has already been indicated heretofore, that has been about the percentage of unsuccessful performance, but there seems to be reason for belief that the percentage might be reduced with the speeding up of the breaker process. Operating performance, however, over the next few years ought to throw further light on this.

The authors were very glad to learn through Mr. Peterson of the work his company is doing toward developing another type of ultrahigh-speed reclosing breaker. While he has not mentioned the operating time for this mechanism, it is to be presumed that it will be as fast or faster than those described in the paper. It will be of considerable interest to learn more about this development and whether the design will permit modernization of existing breakers or will only be applicable to new ones. Actual operating results will also be awaited with interest.

Mr. Prince has reviewed the factors that have to be kept in mind in a system designer's attempts to continue to provide better service while reducing the cost of rendering it. The ultrarapid reclosing breaker seems to be one of the most valuable tools developed in many years that can be utilized in accomplishing this. But, of course, more experience will be required before one will be able to evaluate accurately all its advantages and disadvantages.

Out-of-Step Blocking and Selective Tripping With Impedance Relays

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WHEN two interconnected power systems pull out of step the relative values of voltages and currents are such as to indicate a three-phase fault somewhere in the interconnection, which if in the zone of high-speed impedance or reactance relays will cause them to trip their associated oil circuit breakers. Although this phenomenon has been recognized for some time, and various blocking schemes suggested,[3,4] it has been generally accepted that when high-speed relays are involved, carrier current or pilot wires giving simultaneous control of the relays at both ends of a protected section are required to discriminate between a fault and an out-of-step condition.[2,7] This paper describes a scheme developed for an important tie circuit of the Gulf States Utilities Company, whereby out-of-step blocking and selective tripping are obtained with existing impedance relays and without the use of carrier current or pilot wires.

The Problem

The intervening load between the Neches and Baton Rouge generating stations of the Gulf States Utilities Company is supplied duplicate power by means of a 66-kv sectionalized tie circuit between the two stations as shown geographically in figure 1, and schematically in figure 2. Normally, power is fed into both ends of the line and tapped off to loads at each sectionalizing point. The division of load between the two generating stations varies with the season, depending on the total system load, steam requirements, etc. In case of a fault on this line, the faulted section is segregated and the two systems continue to supply uninterrupted power to the intervening load by operating independently until the fault is cleared and the interconnection re-established.

The high-speed impedance line relays and directional ground relays located at each sectionalizing point clear faults on the tie line with very little disturbance to the loads. However, opening the interconnection may cause an excessive load shift on the two plants, depending on which section is segregated. It is therefore important that the interconnection be opened only when absolutely necessary, and then, if possible, at a selected point.

Transmission-line faults, other than those which can be prevented by reasonable measures, will occur occasionally and must be tolerated. However, in addition to faults, instability occasionally develops due to disturbance elsewhere on the system, and the Neches and Baton Rouge plants pull out of step, causing the relays to open one or more sectionalizing breakers. Opening the interconnection at one point because of an

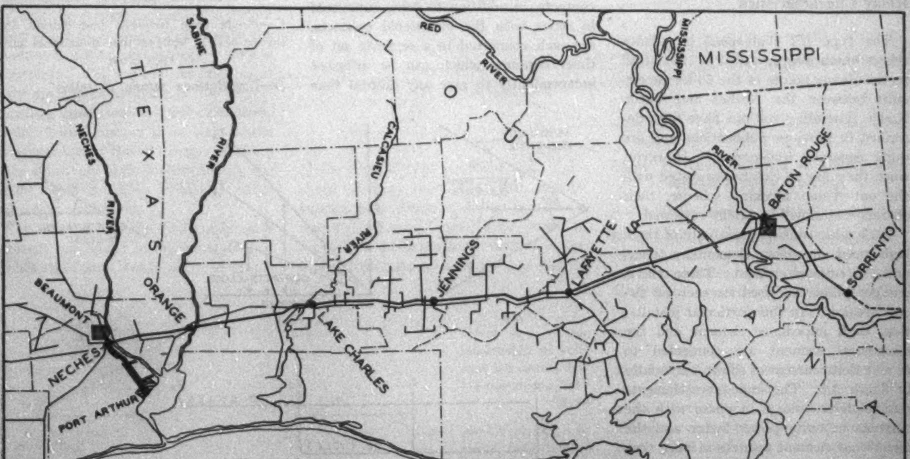

Figure 1. Interconnecting 66-kv transmission circuit between Neches and Baton Rouge steam generating stations

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[1] For all numbered references, see list at end of paper.

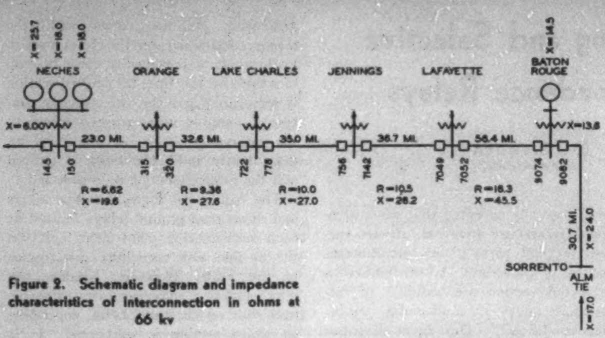


Figure 2. Schematic diagram and impedance characteristics of interconnection in ohms at 66 kv

out-of-step condition does not cause a loss of power to any load but is undesirable because of the usual change in load division between the two systems. Opening more than one breaker in other than one section would cause a loss of all load between the two breakers. The problem was therefore to prevent more than one breaker from opening during an out-of-step condition and to make it possible to select the breaker to be opened under the particular operating condition. Furthermore, it was desired to accomplish the out-of-step blocking and selective tripping with a minimum change to the existing relay equipment and without the addition of carrier current or pilot wires.

Relay Characteristics

The type *HZ* high-speed impedance relays which were installed in 1931 at all sectionalizing points of the 66-kv tie circuits between the Neches and Baton Rouge generating stations have been described in previous publications and are quite generally understood.[1] However, since they are so closely associated with the out-of-step blocking scheme, their characteristics will be briefly reviewed.

Each relay consists essentially of three high-speed impedance elements, a timer, and a directional element. Three relays, one per phase, are used for each oil circuit breaker. In this particular installation, each impedance element and the directional element are connected to receive delta current as shown vectorially in figure 3*A*. The impedance elements receive delta voltage in phase with the currents at unity power factor and the directional element receives voltage that lags the current 60 degrees at unity power factor.

The pull of the current coils tending to close the contacts is opposed by the restraining pull of the voltage coils so that the net force on the impedance elements is proportional to the ratio of voltage to current as shown in figure 3*B*. The curves indicate the relative balance points of the impedance elements, that is, the ratio of voltage to current at which the pull of the current coil just overcomes the voltage restraint. At any ratio less than the balancing ratio the contacts will close and at any ratio greater, the contacts will be held open. Any one of the three impedance elements will close its contacts in one cycle or less for a voltage-current ratio within its balance point. The first impedance-element contacts are connected in series with the directional contacts to close the trip circuit instantly. However, the second and third element contacts, in addition to being connected in series with the directional contacts, are each connected to a separate set of timer contacts which can be adjusted independently to give any desired time delay up to 180 cycles. The timer motor is started by the operation of the third impedance element.

The ratio of the voltage to the current at the relay location during a line fault is equal to the impedance to the fault so that the impedance elements can be set to balance at any desired impedance within their range. As shown in figure 3*D*, the first element Z_1 is set to balance at 80 per cent of the first section impedance, the second element Z_2, at 50 per cent of the second section impedance and the third element, Z_3, at 25 per cent, of the third section impedance. The first element of all relays trips in one cycle or less. The time settings of the relays at the different locations vary from 20 to 35 cycles for the second elements and from 100 to 120 cycles for the third elements.

It is evident from figures 3*B* and *D* that any voltage-current ratio within the balance ratio of Z_1 will close the contacts of Z_1, Z_2, and Z_3. Any ratio greater than the balance point of Z_1, and less than that of Z_2 will close Z_2 and Z_3 contacts. Any

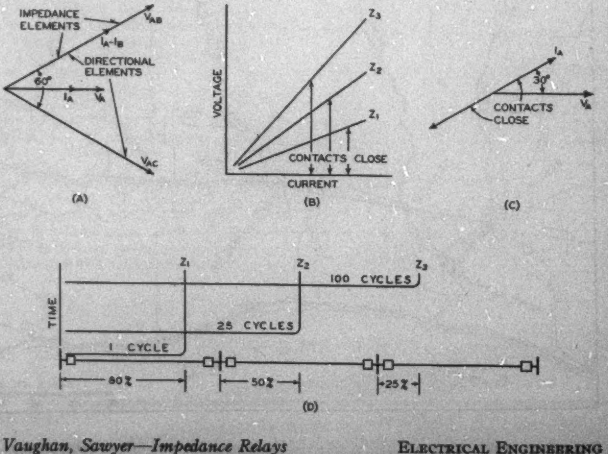
Figure 3. Operating characteristics of HZ impedance relays installed at all sectionalizing points

A—Vector relationship of voltages and currents applied to relay elements at 100 per cent power factor

B—Relative characteristics of impedance elements

C—Angle zone between line current and line-to-neutral voltage that directional contacts close

D—Time-distance setting of relays



ratio greater than the balance point of Z_2 and less than that of Z_3 will close Z_3 only.

The directional element has a true wattmeter characteristic, that is, there will be a closing torque on the contacts when the current applied to the element either leads or lags the applied voltage by less than 90 degrees. Since the directional element is connected to receive delta voltage which lags the applied delta current by 60 degrees at unity power factor, the phase relation of the phase current with respect to phase voltage for a closing torque is 30 degrees lead to 150 degrees lag as shown in figure 3*C*.

From the above, it can be seen that the manner in which the impedance relays operate during an out-of-step condition depends on the ratio of voltage to current, the relative phase angles of the voltage and current, and the length of time that the contacts of the impedance elements remain closed.

Analytical Investigation

In order to determine the effect of an out-of-step condition on the relays at the various sectionalizing points, an analysis was made of system voltages and currents during a complete slip cycle between systems. This information is also supplemented with oscillograms obtained with an automatic oscillograph located at the Neches generating station.

The part of the system considered consists of the Neches generating station at Beaumont, the 66-kv sectionalized tie circuit, and the generating station at Baton Rouge which is normally tied in with the Arkansas-Louisiana-Mississippi system at Sorrento. The impedances in ohms at 66 kv are shown in figure 2. A typical operating condition is two generators, number 1 and number 2, at Neches and two generators at Baton Rouge. Because of the relatively high line impedance the results would not differ greatly for other generating conditions.

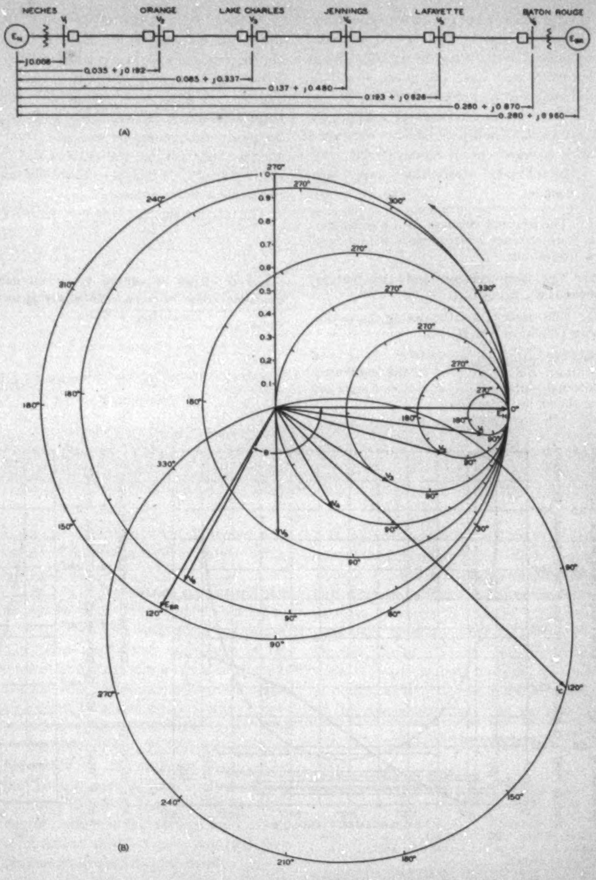


Figure 5. Circle diagrams of current and voltages at relay locations

A—Unit impedances to sectionalizing stations

B—Circulating current I_{c}, and line-to-neutral voltages at sectionalizing stations for complete slip cycle between Neches and Baton Rouge. Vectors are shown for 120-degree displacement angle

The internal voltages (voltage back of transient reactance) of the generators at Neches and Baton Rouge, all of which are of the turbine type provided with high-speed voltage regulators, will remain substantially constant during a fault or out-of-step swing. Also, since power is normally fed into the line at both ends, the internal voltages at both stations will be about equal. The load current or line-charging current during the fault or out-of-step period will be relatively small. When the out-of-step condition is caused by an external fault located near one of the generating stations, the 66-kv bus voltage will drop so that, if the fault is of long duration, it will have considerable effect on the circulating current and line

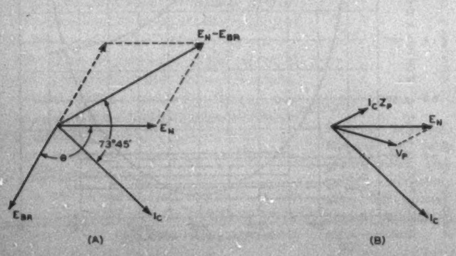


Figure 4. Vector relationship of voltages and current during out-of-step conditions

A—Circulating current I_c for displacement angle θ

B—Voltage at point *P* for circulating current I_c

voltages during the out-of-step condition. However, since the fault would normally be cleared by the time the actual pull-out occurred, and since the effect would be different for each fault location, it was neglected in the analysis. The effect for any special condition can be estimated fairly closely from the curves shown.

The following assumptions were therefore made:

1. The internal voltages of the generators at both stations remain constant and equal in magnitude.
2. The load current and line-charging current are negligible.
3. The effect of a fault during the out-of-step condition is neglected.
4. The unit impedances from the internal voltage, E_N, at Neches to the equivalent internal voltage E_{BR}, at Baton Rouge are as shown in figure 5*A*.

As the two systems swing apart, the difference voltage, $E_N - E_{BR}$, between the internal voltages at Neches and Baton Rouge will cause a circulating current $E_N - E_{BR}/Z$ to flow, where Z is the total impedance between E_N and E_{BR} including the generator transient reactances. The voltage and current will be balanced between phases so that only one phase need be considered.

The relation existing between the internal voltages, the difference voltage, $\boldsymbol{E}_N - \boldsymbol{E}_{BR}$, and the circulating current, $\boldsymbol{I}_c$, is shown vectorially in figure 4*A*. The circulating current $\boldsymbol{I}_c$, which is shown vectorially equal to $\boldsymbol{E}_N - \boldsymbol{E}_{BR}/\boldsymbol{Z}$, may also be expressed mathematically as,

$$\boldsymbol{I}_C = \frac{E(1 - \cos\theta - j\sin\theta)}{Z} \qquad (1)$$

where $\boldsymbol{E}_N$ and $\boldsymbol{E}_{BR}$ have the same magnitude E, and θ is the angle that $\boldsymbol{E}_{BR}$ lags $\boldsymbol{E}_N$. The angle of 73 degrees 45 minutes that $\boldsymbol{I}_c$ lags the difference voltage is the natural impedance angle of the system.

The current $\boldsymbol{I}_c$ will be common throughout the tie circuit and is the current at each relay location for any given displacement angle, θ. However, the voltage will vary with location and at any one point, P, the line-to-neutral voltage is

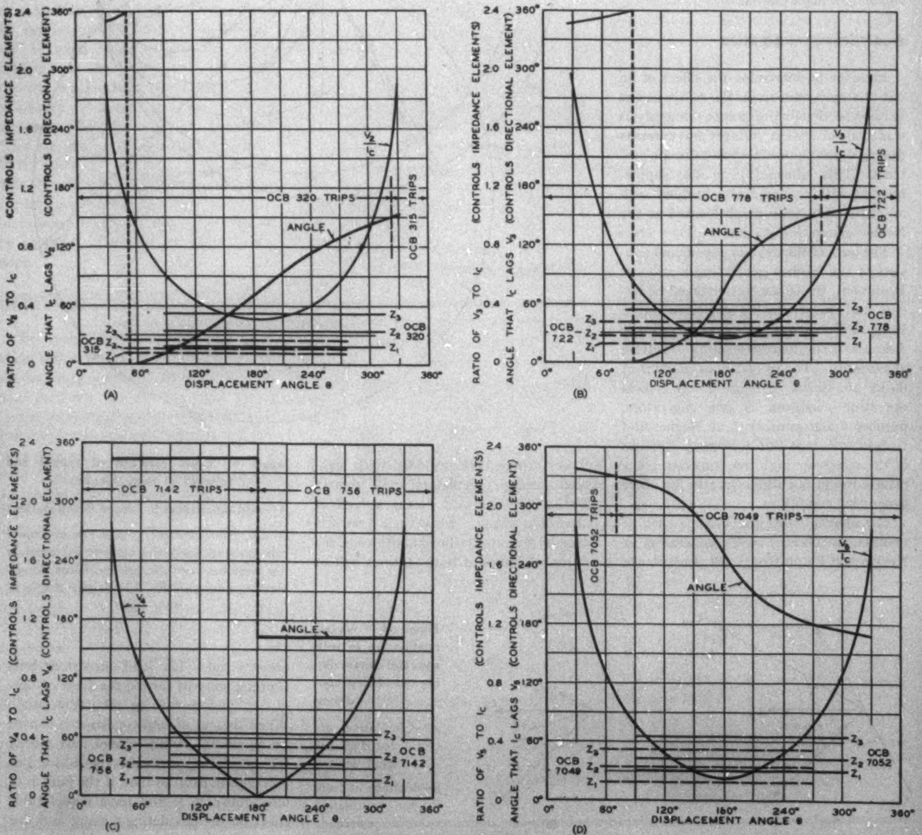


Figure 6. Ratio of voltage to current and operating zones of impedance relays at sectionalizing stations

A—Orange
B—Lake Charles
C—Jennings
D—Lafayette

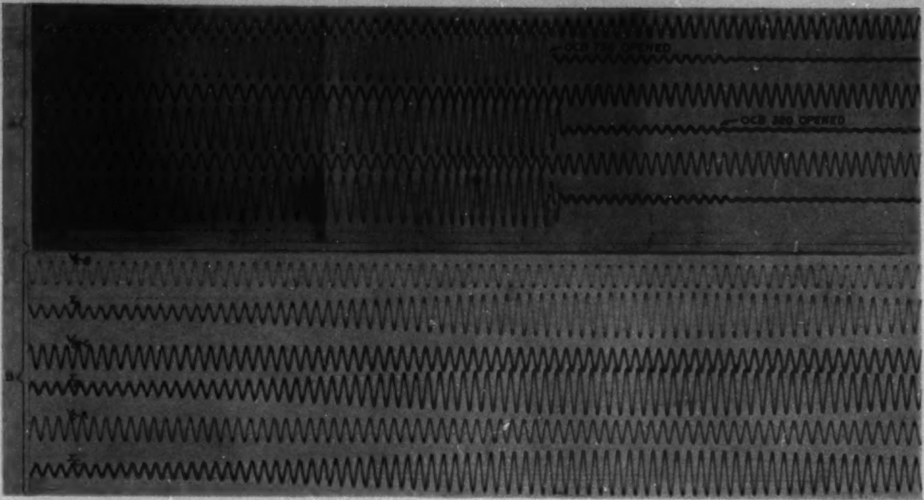


Figure 7. Typical oscillograms of voltage and current at Neches 66-kv bus during system disturbance

A—Out-of-step condition caused by disturbance on Baton Rouge end of system external to interconnections. Breakers 756, 778, 320 opened

B—Severe system oscillations caused by disturbance on Baton Rouge end of system external to interconnection. No breakers opened

equal to $\boldsymbol{E}_N - \boldsymbol{Z}_P$ where $\boldsymbol{Z}_P$ is the impedance from E_N to P. This relation is shown vectorially in figure 4*B*. It may also be expressed mathematically as,

$$\boldsymbol{V}_P = E\left[1 - \frac{\boldsymbol{Z}_P}{\boldsymbol{Z}}(1 - \cos\theta - j\sin\theta)\right] \quad (2)$$

The voltage and current at any point on the line for any displacement angle can be obtained either graphically as shown in figure 4, or analytically by means of equations 1 and 2. The loci of $\boldsymbol{I}_c$ and the line-to-neutral voltage vectors for a complete slip cycle are shown plotted in figure 5*B*. The vectors, shown for 120-degree displacement angle, represent unit values, where unit voltage is normal internal phase-to-neutral voltage, unit impedance is the total impedance between E_N and E_{BR}, and unit current is the current that would flow if $E_N - E_{BR}$ were equal to unit voltage.

It will be noted that the locus of the current vector, $\boldsymbol{I}_c$, is a circle with its center displaced one unit from the origin, that is, at $r - jX$, where r and X are the unit values of resistance and reactance corresponding to Z.

The loci of the voltage vectors will also be circles with their centers located at $1 - Z_P(r - jX)$ units from the origin. The phase angle and magnitude of the current or voltage at a sectionalizing point is equal to a vector drawn from the origin to a point on the respective circle corresponding to the displacement angle. The circulating current, $\boldsymbol{I}_c$, will increase to a maximum at 180 degrees displacement and back to zero as the two systems slip one pair of poles, that is, 360 electrical degrees, whereas the voltage decreases to a minimum at 180 degrees and back to a maximum at zero displacement.

It is evident from figure 5 that the voltages at the generating station 66-kv busses, V_1 and V_6, will not drop enough during out-of-step conditions to cause the relays at those locations to operate. The voltages will, however, drop appreciably at Orange, Lake Charles, Jennings, and Lafayette, particularly at Jennings which is almost exactly at the electrical center of the interconnection. The ratio of the

Switch Position	Switch *A*	Switch *B*	Operation
1	Open	Closed	Nonblocking
2	Open	Open	Out-of-step blocking
3	Open	Closed	Preferred out-of-step tripping

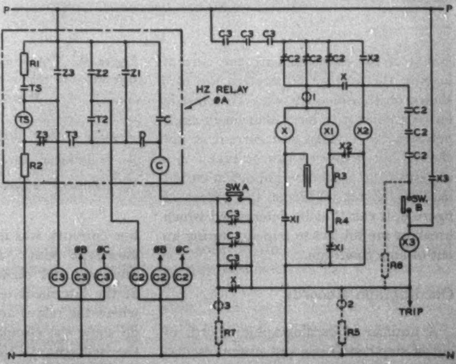


Figure 8. Schematic diagram of relay control circuit. Dotted connections show test connections of oscillograph galvanometers

voltage to current and the phase relation between them for these four points are therefore plotted against displacement angle, in figures 6*A*, *B*, *C*, and *D*. The actual settings of the impedance elements expressed as a ratio of voltage to current, and representing the balance points of the elements with the current lagging the voltage 60 degrees are also shown on the same curves. The shift in balance point with large changes in angle between the voltage and current is not shown, but if desired can be taken into account from available calibration curves on the *HZ* relay. From the curves of figure 6, it can thus be determined which breakers are subject to trip-out during an out-of-step condition.

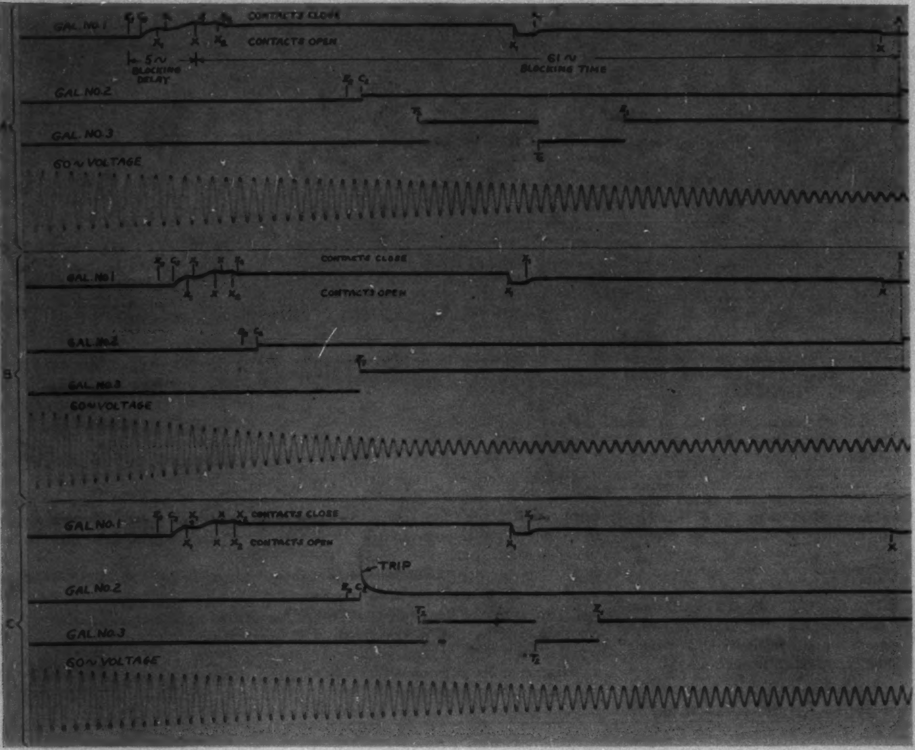


Figure 9. Oscillograms showing sequential operation of relays during simulated out-of-step conditions

A—Out-of-step blocking for slow pull-out

B—Out-of-step blocking for fast pull-out

C—Selective tripping during pull-out

Oscillograph Records

A number of oscillographic records of out-of-step conditions and system oscillations, occuring over several months' operation previous to the installation of the blocking relays, have been obtained by means of an automatic oscillograph located at Neches. The oscillograph, which was connected to record the 66-kv bus line-to-line voltage and the 66-kv tie-line currents, was initiated by an impedance-type relay. Although the oscillograms do not show the actual voltages at the intermediate sectionalizing points where the relays are most affected, they do show the circulating current I_c, and the voltage at Neches. These values can be interpreted from figure 5 and figure 6, to indicate the voltage and phase angles at the sectionalizing points.

Two typical examples are shown in figure 7. Oscillogram *A* shows the results of a pull-out due to a disturbance on the Baton Rouge end of the system, external to the interconnection which resulted in breakers 320, 778, and 756 opening. As shown by the oscillogram, at the time the oscillograph was initiated, the line voltage V_{B-A} was slightly lagging I_A, that is, I_A was lagging V_A by about 120 degrees, which from figure 5, indicates a displacement angle of 260 degrees. It will be noted from figure 6*C*, that at 260 degrees displacement, the Z_3 element of breaker 756 is nearly at its balance point. At the time breaker 756 opened, the current I_A was lagging V_A by about 90 degrees which indicates a displacement angle of 210 degrees, sufficient to cause tripping of the Z_2 element, or possibly Z_1 element.

This also shows that E_{BR} was advancing in phase position with respect to E_N, which might be expected with a disturbance near Baton Rouge. The Z_2 element of breaker 778, and the Z_3 element of breaker 320, both balance at about 220 degrees, and would therefore have closed their contacts shortly before 756 tripped. The total time shown on the oscillogram to the opening of breaker 756 is 39 cycles, which, allowing 15 cycles for breaker operation, would leave 24 cycles or just about the timing of Z_2 for breaker 756. Also, the Z_1 contacts for breaker 756 would have operated about that time, so that either the Z_2 contacts or the Z_1 contacts might have actually tripped the breaker. The timers for breaker 778 would have reached their second-zone contacts before breaker 756 opened and would therefore cause tripping on breaker 778. Breaker 320, which opened 15 cycles after breaker 756, was evidently tripped by its Z_3 contacts, just before 756 opened. Inspection of the relay that tripped breaker 320 showed that the Z_3 timer contacts had undoubtedly closed prematurely due to break contact on the Z_3 element being out of adjustment, which on the early design of *HZ* relay would energize the timer motor.

Oscillogram *B* shows oscillations between Neches and Baton Rouge, also due to a disturbance on the Baton Rouge end of the system. The disturbance in this case was not severe enough to cause the two systems to pull out of step. This oscillogram is of interest because it shows the natural period of oscillation.

Blocking-Relay Scheme

It is evident from the foregoing that the voltage and currents applied to the impedance relays during some part of a slip cycle may have the same relative values as for line faults located within the operating zones of the relays. It is also evident, however, that the ratio of voltage to current gradually decreases so that it comes within the zone of Z_3 first, then Z_2, and finally Z_1 if the relay is located near the electrical center. Relays located farther from the electrical center will close only their Z_3 and Z_2 contacts in succession. Also, since the out-of-step condition produces balanced voltage drops, the impedance elements of all three phases will operate in the order, $Z_3 - Z_2 - Z_1$ and then reset in the reverse order, that is, $Z_1 - Z_2 - Z_3$, to complete the slip cycle.

When a line fault occurs, the ratio of voltage to current at the relay reaches its final value almost instantly and remains substantially constant during the operating time of the relay. The basis of the blocking scheme is therefore the sequential closing of the impedance elements of all three phases during a slip cycle. The operation of the Z_3 elements of all three phases without the immediate operation of a Z_1 element causes the tripping circuit of the Z_1 and Z_2 elements to be blocked out long enough for the displacement angle to pass through the operating zones of Z_1 and Z_2.

The blocking equipment, as shown schematically in figure 8, consists essentially of the three existing *HZ* impedance relays, two special type *SM* auxiliary relays, two type *SG* auxiliary relays, a capacitor, a resistor, and a control switch. The a-c connections to the *HZ* relays have been omitted from the diagram since they have no bearing on the blocking scheme which functions within the 125-volt d-c control circuit.

One of the *SM* relays consists of three instantaneous voltage elements, C_3, each with make and break contacts, and an instantaneous current element, X_3 with make contacts. The other *SM* relay consists of four instantaneous voltage elements, C_2 and X_2, each with make and break contacts. The two *SG* relays, *X* and X_1 are standard voltage relays used with the capacitor and resistor to provide time delay. The control switch is a three-position switch which can be set to obtain nonblocking, out-of-step blocking, or preferred out-of-step tripping.

When out-of-step blocking is desired, the switch is set on position 2, so that contacts *A* and *B* are both open. As the systems pull out of step and the voltage-current ratio comes within the zone of the impedance relays, the three Z_3 contacts will close, thus energizing the three C_3 contactors which will open their break contacts connected in parallel in the trip circuit and close their make contacts which are all connected in series. The closing of the three C_3 make contacts will energize the *SG* relay, X_1, from positive through the C_3 contacts, the C_2 break contacts and the X_2 break contacts to negative. The capacitor will be partially charged through the *X* coil, but not enough to pick up *X*. The closing of the X_1 contacts will energize the other *SG* relay, *X*, which will open its break contact in the trip circuit. It will also close its make contact to energize contactor X_2. When the break contact of X_2 opens, the coil of *SG* relay, X_1, will be disconnected from negative. However, the charging current to the capacitor will delay its opening several cycles. When X_1 make contact opens, the *X* coil will be disconnected from negative but its drop-out will also be delayed several cycles due to the capacitor charging in the reverse direction. The capacitor-resistor arrangement shown in the diagram will provide approximately 5 cycles delay in the opening of the *X* break contact after Z_3 contacts close and will keep it open approximately 60 cycles, giving an over-all blocking time of approximately 65 cycles.

When the displacement angle reaches the zone of the Z_2 elements they will operate and energize the C_2 contactors which will open their break contacts and close their make contacts. However, with switch *B* open, the C_2 make contacts will have no effect and by that time

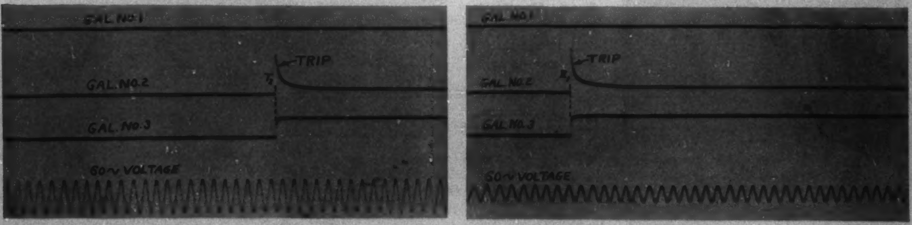


Figure 10. Oscillograms showing operation of relays during simulated fault conditions

A (left)—Three-phase fault in zone of Z_2 and beyond zone of Z_1

B (right)—Three-phase fault in zone of Z_1

the X_2 make contact will be closed so that the opening of the C_2 break contacts will have no effect. Also, during the time the X break contact is open, the trip circuit will be open to Z_1 and the timing circuits of Z_2 and Z_3.

When a single line-to-line fault occurs in any one of the impedance zones, neither all three C_3 elements nor all three C_2 elements will pick up and the *HZ* relays will function in their normal manner. In case of a three-phase fault in the first or second impedance zone, the Z_3 elements will operate and pick up all three C_3 elements. However, the C_2 break contacts will open before relay X picks up and prevent any blocking action. If a three-phase fault occurs in the zone of Z_3, the blocking period will be over before the timing period of T_3 elapses and normal tripping will be obtained. If a fault occurs in a blocked section during the out-of-step period, tripping will be delayed until the end of the blocking period.

When preferred out-of-step tripping is desired, the control switch is set on position 3, which opens switch contacts A and closes switch contacts B. The operation of relays will be the same except that when the C_2 make contacts close the trip circuit will be completed through control switch contact B, and the breaker will be tripped without waiting for the directional contacts and either T_2 or Z_1 contacts to close. This is important as the interconnection is opened up at the desired point as soon as the out-of-step zone reaches the Z_2 elements without any respect to the directional element or timing of Z_2, so that the system disturbance is minimized. Fault tripping is obtained in the normal way.

When the switch is in the nonblocking position 1, the blocking contacts are shunted out by contacts A, and contacts B are open, so that the blocking relays have no effect on the operation of the *HZ* relays.

The dotted connections in figure 8 show the scheme that was used to test the timing and sequential operation of the combined relay equipment with an oscillograph. The number 1 galvanometer of the oscillograph recorded the closing of the Z_3 contacts and the sequential operation of the X_1 and X relays. The number 2 galvanometer recorded the closing of the Z_2 contacts by measuring the current flowing through the resistor, R_4, in series with the resistor R_5. It also recorded when the trip circuit closed by the higher deflection caused by the current through R_5 only. The number 3 galvanometer recorded the operation of the Z_1 contacts.

In making the tests, actual out-of-step conditions were simulated as closely as possible. The current coils of the *HZ* relays were energized with a constant 60-cycle current of 8.5 amperes. By means of a variable-voltage test set, the voltage coils were energized with a 60-cycle voltage that could be varied at a rate corresponding to the change in voltage-current ratio during an out-of-step condition. This voltage which was recorded by the number 4 galvanometer was also used as a timing indication on the oscillograms.

Typical results of the tests are shown in figure 9 and figure 10, which show respectively the action of the relays during out-of-step conditions and during three-phase faults within the operating zones of the impedance elements.

The oscillogram in figure 9*A*, which was taken with the control switch on position 2, for blocking, shows the sequential operation of the relays for a relatively slow slip cycle. It will be noted that a delay of five cycles is obtained between the closing of the Z_3 contacts and the

Figure 11. View of relay panels

A (left)—Two sets of auxiliary blocking relays with covers removed from one set

B (right)—Station switchboard with two sets of *HZ* impedance relays on middle panel and blocking relays on auxiliary panel to the left opening of the X break contact in the trip circuit. This is to allow time for the Z_1 or Z_2 contacts to close in case of a three-phase fault within the section and thus not delay normal tripping. The blocking period from the opening of the X break contacts until it closes again is recorded as slightly less than 61 cycles. It will be noted that the number 3 galvanometer recorded the closing of the T_2 timer contacts which occurred before the Z_1 contacts closed.

The oscillogram in figure 9*B* was taken under the same conditions as figure 9*A*, except that the 60-cycle voltage was decreased faster to represent a rapid pull-out. In this case the Z_1 contacts closed before the T_2 contacts.

The oscillogram in figure 9*C* was taken with the control switch in position 3, for preferred out-of-step tripping. As shown by the number 2 galvanometer tracing, the trip circuit closed immediately after the Z_2 contacts picked up and before the T_2 or Z_1 contacts closed.

The oscillograms in figure 10 were taken with the control switch in position 2, for blocking. In *A*, a voltage was applied to the impedance elements corresponding to a three-phase fault in the second zone. In *B*, the voltage applied was equivalent to a three-phase fault in the zone of Z_1. Both oscillograms show that the blocking relays did not pick up, thus permitting the impedance elements to trip in their normal manner.

The complete installation consists of eight sets of blocking equipment, that is, two each at Orange, Lake Charles, Jennings, and Lafayette. The only change necessary to the *HZ* relays was to modernize them by providing two additional studs and a switch-controlled timer as shown in figure 8. A view of two sets of the auxiliary blocking relays mounted on an auxiliary panel section is shown in figure 11*A*. The covers have been removed from the set on the left to show more clearly the different elements of the relays. The selector switches are located between the two sets of relays, as shown. The capacitors and resistors are mounted on the back of the panel. Figure 11*B* shows a view of a complete installation at one station consisting of two sets of *HZ* relays on the two upper sections of the middle panel, and the two sets of auxiliary relays on the middle section of the left-hand panel.

Conclusion

The method used for calculating line voltages and currents provides a means of determining the performance of distance relays during out-of-step conditions. The automatic oscillograph is also invaluable in studying voltage and current characteristics during the slip cycle.

Out-of-step blocking of high-speed impedance and reactance relays has been available where carrier current or pilot wires are used as a medium of control. The scheme described in this paper can be readily applied to existing installations of impedance relays or used with new installations where carrier current or pilot wires are not available. In addition to blocking, the scheme provides a means of rapid tripping during out-of-step conditions at any desired location which can be selected by means of a selector switch. At the time of writing this paper the equipment was just being installed and had not been put in operation. However, the rigid field tests that were made with simulated out-of-step conditions indicate that the scheme will function as intended.

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Discussion

E. H. Bancker (General Electric Company, Schenectady, N. Y.): For some five or six years prior to 1934 there were many studies of stability in which the effect of relays upon system stability was an important factor. In reference 3 Mr. Hunter and the writer undertook to study the reverse of this situation and to find out what effect instability had upon relays. This was further explored by Mr. Mason in his paper "Relay Operation During System Oscillations," which appeared in volume 56, July 1937, Electrical Engineering, page 823. Reference 2 outlines a study of a specific system from both points of view.

During the course of the investigation of possible means for preventing incorrect relay operation during instability, a scheme was devised which is mentioned briefly on page 194 of reference 2. This scheme is covered in more detail in United States Patent No. 2,030,665. This arrangement is intended particularly for application to reactance-type distance relays and consists in changing the characteristics of the starting unit after the started unit has operated. It prevents relay operation during a system swing when conditions are similar to those existing during a fault, and yet permits relay operation under actual fault conditions.

This paper presents an interesting application to distance relays alone of the principles now in use as a result of these earlier studies for blocking tripping of carrier pilot relaying during system oscillations.

In June 1936 there was published a French patent No. 799,279 which disclosed an arrangement for preventing unwanted operation of impedance relays by utilizing the progressive drop in indicated impedance during a slip cycle in contrast with the immediate drop that occurs when a fault starts.

This paper is an interesting sequel to these others in giving the details of another actual installation and its characteristics during loss of synchronism and in giving in detail the application of the principles now in use, and those outlined in the French patent. Of special interest is the oscillographic record of actual cases of loss of synchronism and bad system oscillations. Such records, in conjunction with the mathematical analysis, make possible still more refinement in designing and selecting protective apparatus in such a way as to increase service continuity.

In view of the very complete research which has already been made and described regarding relay operation during system oscillations not accompanied by a fault on the system, it is regrettable that the authors have neglected to analyze the possible effects of the presence of such a fault during the oscillations. It is fairly obvious that with such a fault, all three phases will not be similarly affected. It is very likely that the Z_3 impedance element of one phase will operate in a much different fashion from the Z_3 elements in the other two phases. How this will affect the functioning of the scheme described by the authors, wherein the simultaneous operation of all Z_3 elements has been assumed, should be analyzed carefully to prove its dependability under all practical operating conditions. It is to be hoped that a sequel to this paper will appear with the oscillographic evidence to indicate the success attained.

H. R. Vaughan: Mr. Bancker's discussion emphasizes the statements made in the opening paragraph of the paper regarding the previous recognition of out-of-step phenomena and the generally accepted conclusion that carrier current was required to prevent out-of-step tripping where high-speed relays were involved.

Even before 1934, the effects of instability on distance-type relays were quite well recognized. In 1932, I had an opportunity to assist in investigating on the network analyzer, the instability influences on distance-type relays in operation on a specific system. The results of the investigation showed conclusively that certain conditions of instability would cause the relays to operate and accounted for questionable relay operations that had been experienced. This condition was overcome by speeding up other relays to prevent instability. The paper that Mr. Bancker and Mr. Hunter presented in 1934 as well as the later papers referred to are valuable contributions toward a better understanding of the effects of out-of-step conditions on distance-type relays.

Mr. Bancker refers to a scheme intended particularly for reactance relays that was mentioned briefly on page 194 of reference 2 and covered in more detail in United States Patent No. 2,030,665. It is stated on page 194 of reference 2 that the scheme appeared doubtful and that carrier-current control was adopted instead, thus bearing out the statement in our paper that carrier current was considered necessary to provide out-of-step blocking.

Regarding the effects of the presence of a fault during system oscillations, it is recognized that the majority of pull-outs are caused by faults. However, as stated in the paper, the fault would normally be cleared by the time actual pull-out to the point of relay tripping occurred, so that the operation of the blocking relays would not be appreciably affected. This is borne out by the automatic oscillograms, two of which are shown in the paper. The voltages and currents shown by these oscillograms which were taken during pull-outs caused by system faults external to the interconnection, check closely the values calculated by neglecting the effects of the fault.

The effects of long-duration faults external to the interconnection could be readily determined by means of the a-c network analyzer, or more laboriously by calculations. In general, the electrical center of the interconnection would be shifted toward the fault. If the fault were phase to phase, the fault current fed through the interconnection might cause the Z_3 element of the relay associated with the faulted phases to pick up. However, the generators nearest the fault would normally advance in phase angle so that the circulating current due to the out-of-step condition would counteract the current supplied through the interconnection to the fault. This would tend to equalize the impedances indicated to the three relays so that all three Z_3 elements should pick up before any one relay could cause tripping.

The blocking scheme is based on all three Z_3 elements being in the operated position at one time, but it is not necessary for them to pick up simultaneously. The pick up of one or two Z_3 elements before all three Z_3 elements picked up would not prevent blocking. It is only necessary that all three Z_3 elements be in the operated positions before one of the Z_1 contacts and its associated directional contact close simultaneously, or before one of the Z_2 contacts and its associated timer and directional contacts close at the same time. It is believed, therefore, that the blocking relays will function properly even though an external fault exists at the time of an out-of-step condition. As operating experience and additional oscillographic data are collected it may be necessary to alter some of the Z_2 and Z_3 settings or to change the timing periods of the blocking relays.

Improvements in the Construction of Condenser Bushings

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Synopsis: Condenser bushings use paper to provide high dielectric and physical strength. The value of paper as an insulation is recognized by its accepted use as the insulating medium in cables, transformers, and other apparatus. It is also recognized that unlimited life is attained when proper protection is provided against external influences. Such protection is obtained by improved methods of winding the capacitors, treatment with oil impregnation, and surface varnish. Further protection is provided for outdoor bushings by sealing the condenser in a weather casing of porcelain with improved flexible caps and gaskets. Insulating oil or a plastic heavier than water is available for encasing the capacitor.

MANY thousands of transformers and circuit breakers installed during the past 30 years have been equipped with condenser-type bushings. This type of construction has been used here and abroad because first, the distribution of the voltage stresses through the bushing is such as to lower the concentration of such stresses and thereby increase the resistance of the bushing to dielectric breakdown, and second, it has great mechanical strength and resiliency. The condenser bushing is composed of paper and an organic bond. Here, as in transformers, capacitors, cables, and other high-voltage apparatus, paper provides the high mechanical strength and high electrical, especially impulse strength. In winding the bushing the paper is divided into a number of condensers by the insertion of foil layers at intervals selected to provide the proper distribution of the voltage stresses. These well-known principles have been in use since the first condenser bushings were manufactured.

It is recognized that the life of paper as an insulating medium is without limit as long as it is retained in its original state. The greatest enemy to the life and dielectric strength of such insulation is moisture. The manufacturer and the user have both aimed for such improvements as would definitely retain the original characteristics of the paper. Recent improvements in the construction of condenser bushings have markedly increased their resistance to the effects of moisture.

In a condenser bushing, the condenser—or core, as it is sometimes called—is the insulation member. The first step in improving the moisture-resistant characteristics of the bushing is to make the condenser tight and homogeneous. This was found to be a matter of processing, requiring a definite proportionment of bonding material to the weight of the paper, as well as a more rigid control of the relative speed, pressure, temperature, and tension during the winding process. That such tight bushings can be made is indicated by the fact that in

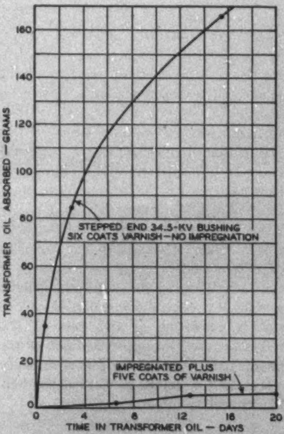

Figure 1. Effect of oil impregnation in preventing oil travel in condenser bushings

Condensers immersed in transformer oil at 80 pounds per square inch and 80 degrees centigrade

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commercial production, bushings must withstand a pressure test of 60 pounds per square inch without leaking.

A polymerizing organic oil is now used to impregnate the condenser to considerable depth in order to increase its resistance to moisture. The condenser is then cured by an appropriate time and temperature process, which converts the oil from a liquid into a permanent solid by a dual process involving both oxidation and polymerization. This treatment also increases the effectiveness of the varnish by providing for it an improved base.

The oil used for impregnating the condenser was selected after an exhaustive investigation of many materials. The choice was made on the basis of its power of penetration, ease of curing, electrical characteristics, and effectiveness as a seal against both oil and water. Comparative data were obtained by testing sample 34.5-kv bushings with various impregnating materials, times of curing, and other processing details. These data would be interesting from the viewpoint of chemistry or physics, but for the present purpose it should be sufficient to say that the oil now in use was found to be superior in the essential features.

The effectiveness of the impregnating oil treatment on sealing the pores of the condenser is shown by figure 1. The data for these curves were obtained by immersing duplicate bushings in transformer oil at 80 degrees centigrade, with an applied pressure of 80 pounds per square inch, for 19 days. The weights of the bushings were measured at intervals in order to determine the progressive absorption of the hot oil. The oil-absorption capacity of the untreated bushing was determined by test and calculation to be slightly greater than 400 grams, so the absorption of approximately 6 grams by the treated bushing after 19 days must be regarded as negligible. This test is very exaggerated and is no measure of the absorption of the bushing under ordinary operating conditions, but serves under accelerated conditions to demonstrate the relative improvement obtained by the new oil-impregnating treatment.

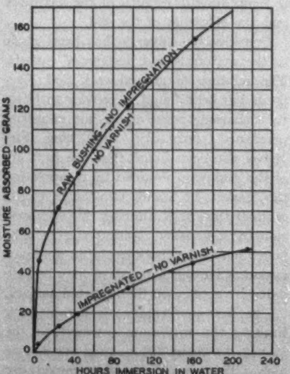

Figure 2. Effect of oil impregnation on rate of moisture absorption; 34.5-kv condensers stepped on one end, immersed in water

Similar tests were performed to determine the effect of the oil impregnation on the absorption of free moisture. Sample bushings were immersed in water, and weighed at intervals to observe the progressive absorption. Of the various tests performed, data showing the relative performance of the impregnated, unvarnished condenser and that of the raw condenser, untreated, were selected for figure 2. In the untreated condenser the moisture is absorbed rather rapidly at first, and then at a decreasing rate. The treated condenser shows a marked reduction in the initial rate of absorption and further slowing up of the absorption process after a few days. This curve indicates that after 19 days total immersion in water the absorption by the condenser was only about one-eighth of its theoretical capacity of approximately 400 grams.

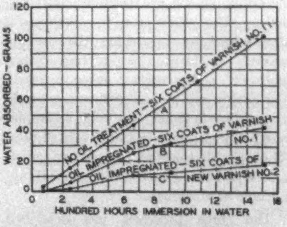

Figure 3. Effect of improved varnish blend and effect of oil impregnation as measured by moisture absorption; 34.5-kv bushings stepped on one end, immersed in water

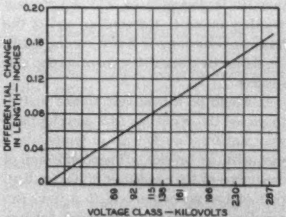

Figure 4. Approximate change in length between condenser core and porcelain casing of bushings of various voltages for 100 degrees centigrade change in temperature

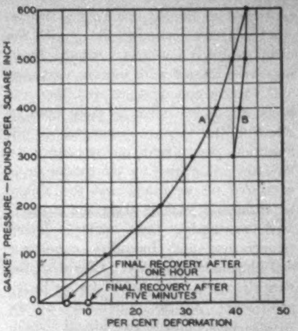

Figure 5. Deformation test on cork-Neoprene gasket material showing compression and return toward original dimension

Another interesting accelerated test was performed by testing bushings under oil at pressures of 800 pounds per square inch. After two hours of such treatment the bushing with only the varnish treatment absorbed ten grams of oil, whereas the oil absorbed by the impregnated bushing was too small to measure.

Obviously, such severe tests serve only to determine and illustrate the efficiency of the impregnating oil treatment in resisting moisture penetration of the condenser, and reflect actual operating conditions only in a greatly exaggerated way.

After the impregnating oil had been selected, research was directed toward obtaining a superior varnish treatment for the surface. The following are some of the more important characteristics which were sought:

(*a*). High resistance to electrical leakage over the surface.

(*b*). Resist the tendency to "tree" or "track" under high potential stress.

(*c*). Seal the bushing against the penetration of moisture, oil, ordinary acid fumes, etc.

(*d*). Resist abrasion such as is met with in normal handling.

(*e*). Provide a hard, smooth surface to avoid holding of dust, carbon and other foreign substances and to facilitate cleaning.

(*f*). It must not crack or craze from age or temperature changes.

Many varnishes show good oil-resistance characteristics, so work was concentrated on finding one having the desired moisture resistance along with the other required qualities. Sample bushings were treated with various varnishes and varnish combinations and then exposed to tests similar to those used in selecting the type of impregnating oil. Selection was based on resistance to moisture absorption by the condenser as measured by weighing, and the ability to withstand various tests and accelerated weathering tests under varying temperature and humidity conditions and ultraviolet exposure. Of course, the varnish must be suitable for ordinary processing. As no commonly known varnish was found to provide all the desirable features, a blend was compounded of materials having individual superiorities, so that the new varnish shows superiority in all requirements. The results of the tests on water absorption are shown in figure 3. Curve *B* shows by comparison with curve *A*, the improvement obtained by adding the oil impregnating treatment to the old varnish treatment. Curve *C* shows the further superiority of the new varnish treatment over the old. The moisture absorption is reduced to about 40 per cent of that in older bushings, by the impregnating oil treatment, and further reduced to less than 20 per cent by using the new varnish blend. An interesting feature of these tests is that even after 63 days total immersion in water, the power factor of the bushing with the improved impregnating and varnish treatment was only 3.36 per cent—still an operative bushing.

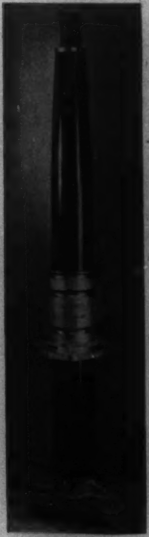

Figure 6. A 23-kv condenser bushing—indoor service

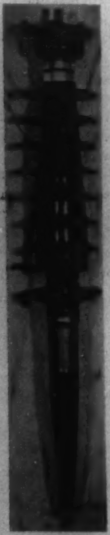

Figure 7. A 69-kv condenser bushing—outdoor service

Treeing, tracking, and crow-footing are terms which have been applied to the phenomenon of creepage occurring on insulating surfaces when the latter are subjected to abnormal electrical stresses. It appears to be initiated by a leakage current along the surface with local concentrations of heat, resulting in gradual thermal breakdown or carbonization of the surface and possibly resulting in the formation of a conducting path. The American Society for Testing Materials test has been found most reliable for determining the arc-resistant characteristics. The resistance to tracking is determined by measuring the time in seconds to form a conducting carbon path on a dry surface when a small, low-energy arc plays continuously across the surface between two point electrodes one-half inch apart, resting on the surface. The varnish selected has an arc resistance equal to the best of the materials applicable as a varnish.

The three processes just described namely, tightness, oil impregnation, and varnish treatment, applied to indoor bushings, provide the moisture-resistance characteristics necessary for the most humid atmospheres. For outdoor bushings, it is desirable to add a porcelain weather casing to the exposed end of the bushing, clamping it down on the bushing flange by a suitable expansion cap and gaskets.

It would be a relatively simple matter to encase the condenser in a porcelain if it were not for the changes in temperature met with in service. The coefficient of expansion of the condenser is greater than that of the porcelain. With a rigid cap coupling between the condenser conductor and the porcelain this difference would be enough to release the pressure on the gaskets at extremely high temperatures.

Figure 4 indicates the differential expansion for bushings of various service voltages. This difference in expansion is taken care of by providing a flexible coupling between the condenser conductor and the porcelain. In the simplest form this resiliency is provided in the cap by shaping it so as to supply the necessary spring action over the range of temperature. In other assemblies the spring element is provided by a separate spring or group of springs enclosed within the cap. With any type of cap it is necessary to design for sufficient length of spring action so that at the lowest temperatures the pressure on the assembly is not excessive, while at the highest temperature, when the differential expansion is the greatest, there remains sufficient pressure to maintain the rigidity of the assembly and the efficiency of the seal.

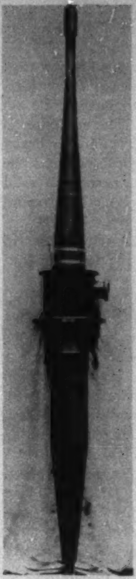

Figure 8. A 138-kv condenser after oil impregnating treatment

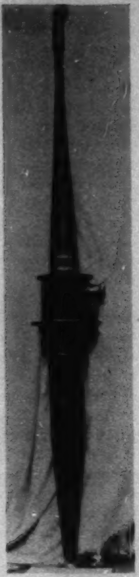

Figure 9. Same as figure 8 except cleaning and applying the varnish

Considerable advance has been made in the materials and designs of gaskets. The mixture of ground cork and Neoprene has been found to provide satisfactory characteristics of oil and moisture resistance, flexibility, and long life. It has also been found that the best life of the gasket is obtained by compressing the gasket to about two-thirds of its original thickness, limiting this compression by a so-called "gasket stop." The latter may take the form of an auxiliary gasket of harder material, or may be provided by a ridge on the gasketed surface.

The best performance is obtained by limiting the maximum pressure on the gaskets to about 300 pounds per square inch. This has been determined by applying various loads and measuring the ability of the gasket to return to the original dimension.

Figure 11 (above). Outdoor condenser bushing assembly being removed from dry-ice bath during temperature-change test

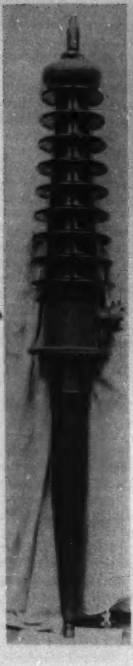

Figure 10. Same as figure 8, completely assembled with weather casing and cap

Figure 5 shows the deformation characteristics of gaskets made from ground cork and Neoprene. The unlimited compression of sample gaskets was measured under various loadings up to 600 pounds per square inch. The return curve *B* was obtained by releasing the pressures, taking readings down to 300 pounds per square inch. Five minutes after pressure was completely released the gasket had returned to within ten per cent of its original thickness and one hour after pressure was released the gasket had returned to within five per cent. It is well known, of course, that with lower pressures, the return toward the original dimensions becomes greater. The pressure of 300 pounds corresponds to about one-third compression, which determines the relative size of gasket stop. The area of the gasket is, therefore, designed to obtain a maximum pressure under lowest temperature and full compression of the spring of approximately 300 pounds per square inch. The data shown in figure 5 illustrate the ability of the gasket to withstand abuse. However, the use of a gasket stop and spring pressure maintained from the cap insures that the gasket is kept at a constant dimension and under a constant pressure. This eliminates any movement of the gasket under temperature change and so contributes to its long life and high efficiency as a seal.

Insulating oil and plastic materials are used for filling the space between the condenser and the porcelain weather casing. A new plastic material heavier than water and highly moisture resistant has been developed for this purpose. In addition to the high specific gravity, other requirements must be met by the material in order to make it suitable for use in bushings. Among the more important are:

1. Specific gravity greater than water throughout the temperature range
2. High dielectric strength
3. Low moisture absorption
4. Not be too fluid at operating temperatures
5. Be plastic at low temperatures
6. Good adhesion to both the condenser and the porcelain
7. Sufficient fluidity to permit easy filling of the bushing

In addition, the material must be stable and neutral in its effect on condenser finishes, gasket materials, and metal parts.

The new plastic material, which has these characteristics, has been tested in the laboratory, and in outdoor service in bushings and with moisture present. In the laboratory tests, 34.5-kv bushings have been operated for over a year with water on top of the filling material, with 70 degrees centigrade flange temperature to soften the compound and at 30 kv. No change was detected in the power factor of the bushing, showing no moisture absorption. In addition, the material itself does not absorb any measurable quantity of moisture.

This material is quite plastic at temperatures as low as −40 degrees Fahrenheit, and will not pull away from the condenser or the porcelain until the temperature has gone down to below −60 degrees Fahrenheit. The material remains sufficiently viscous at 70 degrees centigrade to prevent convection currents, but still can be poured at a temperature of 100 to 125 degrees centigrade.

In addition to the laboratory tests, a large number of bushings using this new filling material have been exposed to the weather for almost a year, operating at a voltage corresponding to the line-to-line voltage instead of line-to-ground voltage. In some of these the caps have been opened up to permit free entrance of moisture to the top of the bushing and some had water introduced on top of the compound at the beginning of the test. Others were sealed up in the conventional manner. This continued operation under higher-than-normal voltage confirms all the laboratory tests, insuring that moisture entering accidentally will be retained in a harmless location at the top

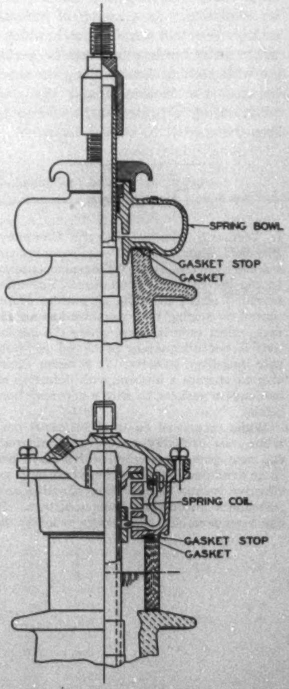

Figure 12. Types of caps showing spring action to maintain rigidity of the assembly and effectiveness of gasket seal

of the bushing and will not get in contact with the condenser itself.

A conventional 115-kv oil-encased bushing with a weather casing containing ten quarts of oil and two quarts of water was operated continuously with 132 kv, twice normal voltage to ground, applied between the bushing terminal and the grounded flange. The bushing stood this test with no measurable change in power factor, so the test was concluded after 60 days.

The primary purpose of these developments was to produce a condenser core which would resist the penetration of moisture. This has been obtained by means of materials, processes, and surface finish. The second step in the development, applicable to outdoor bushings, was to design an assembly which would be effectually sealed against the entrance of moisture to the condenser. This is a matter of proper porcelain, gasket, and cap design. With these conditions fulfilled, it matters little whether the space surrounding the condenser is filled with oil or compounds as this is not required for insulation. As a matter of interest, we have been told of a situation in which a whole set of outdoor bushings is operating with nothing but air filling the space between the condenser and the porcelain, using a heater at the flange to keep the air dry.

Discussion

L. Wetherill (General Electric Company, Pittsfield, Mass.): Mr. Peterson makes the statement that moisture is the greatest enemy to the life of paper insulation. The facts involved might be more accurately represented by stating that moisture has an adverse effect only in cases where the insulation is not adequately protected by suitable long-lived gaskets. It is never desirable to operate a bushing with defective or inadequate gaskets, or with a defective porcelain.

While occasional cases of fractured porcelain can probably never be eliminated, the new gasket materials which have become available in the last ten years offer an effective means of providing effective and permanent protection from moisture. It has been possible to eliminate troubles on the older bushings in service by regasketing. Experience over the last ten years, involving hundreds of thousands of gaskets, strongly indicates that gasketing is no longer a major problem on bushings of modern design.

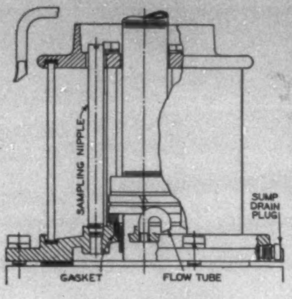

Figure 1. Thermal seal

The experience of the writer agrees with that of Mr. Peterson in that proper control over the materials and conditions during the winding of bushing cores will give a solid and impervious structure. It is the practice of the General Electric Company to require that solid bushing cores must withstand a gas-pressure test of 80 pounds per square inch applied for ten minutes. Experience has shown that a test of this severity assures high quality and long life in service.

There is one additional phase of the differential thermal expansion problem not mentioned by Mr. Peterson. In bushings using solid cores, it is the practice of the General Electric Company to use insulation with coefficient of thermal expansion matched with that of the copper conductor, in order to eliminate internal strains in the core. Such procedure means that a core which is initially tight will remain tight in service.

Mr. Peterson has found that the use of 300 pounds per square inch maximum gasket pressure and about 33 per cent gasket compression give best results. These conclusions are influenced doubtless by the composition and configuration of the gaskets involved. For example, tests on a somewhat harder mixture of cork and Neoprene show that the pressure required for 17 per cent compression varies from 1,100 to 1,900 pounds per square inch, depending upon the dimensions of the gasket.

The trend toward the use of fluid filling compounds in higher voltages is apparently continuing. Fluid compounds do not form shrink voids or show cumulative deterioration as a result of occasional local overstress. They also avoid the danger formerly resulting from the use of solid filling compounds which permitted defective gaskets to remain in service unrecognized.

On the larger oil-filled bushings the General Electric Company, for nearly three years, has been using an open ventilated construction but with the oil protected from the atmosphere by a thermal trap similar in its effect to the conservator used on many power transformers. This construction is shown in figure 1 of this discussion.

The inverted U tube, which connects the bushing with the expansion chamber, serves to prevent circulation of oil by convection currents; and the interchange of oil between the bushing and the expansion chamber is limited to the small amount necessitated by volumetric thermal expansion of the oil. Extensive accelerated tests have shown that bushings utilizing this construction retain their original dielectric condition permanently.

A. J. A. Peterson: Mr. Wetherill's discussion emphasizes, in an interesting manner, the approach of another manufacturer to the problem of protecting the bushing so as to give it longer life. Testing pressures, operating stresses on gaskets, and so forth are matters of individual and detail design. It is interesting to note, however, that the sufficiency of pressure testing to determine sound cores is influenced by the time during which such pressures are applied. Long experience in manufacturing and testing condenser bushings has led to the adoption of combinations of pressure and time to insure the most satisfactory results.

As pointed out in the paper, the numerous improvements in condenser bushings have made the same condenser core suitable for either fluid or plastic encasing material. Both oil and plastic as used in condenser bushings eliminate shrink voids referred to by Mr. Wetherill, and the condenser principle inherently avoids the local overstresses which might be present in other designs.

Gaskets serve not only to keep moisture out of the bushing but also to keep the filling material in the bushing. This is of major importance in bushings where the oil contributes or forms the main part of the insulation, and is obviously of less importance in the capacitor bushing.

There is likewise considerable difference in the relative importance of the filling material of various types of bushings. The condenser unit of a Westinghouse bushing is the real insulating medium and the oil or plastic serves only to protect the condenser, and does not contribute materially to the dielectric strength of the bushing.

Dielectric Strength of Porcelain

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FUNDAMENTALLY, the voltage-time characteristic of insulation suggests the extending of studies for fullerboard and transformer oil[1,2] to other insulation materials. Porcelain is considered in this investigation since it is used extensively for line and substation insulation, in apparatus design as bushings,[3] and for other insulation.

The determination of the impulse characteristics of porcelain for limited and for repeated voltage applications is another object of the paper. Tests were made with full and chopped waves and with steep impulses to simulate traveling waves and direct strokes. Line apparatus in particular frequently is subjected to these two types of impulses.

Test Method

For the impulse tests the equipment and general procedure conform to the usual practice. Voltage and time were recorded by the cathode-ray oscillograph connected across the test object through a resistance divider or a capacitance divider calibrated against the resistance divider. A rod gap chopped the impulse to the desired wave for the steep-front and chopped-wave tests applied to the specimens.

The voltage supply for the 60-cycle tests was a 150-kv 75-kva testing transformer excited through an induction regulator for voltage control. The voltage measured at the voltmeter coil of the testing transformer was calibrated against a standard sphere gap connected across the test load.

Porcelain Shells—Test Results

Forty-seven porcelain shells of the suspension-insulator type were tested in transformer oil at 24 degrees centigrade. The shells were nine inches in diameter and one-half-inch thick between the line electrode and ground plate, figure 1.

Tests were made to determine:

(*a*). The impulse strength for limited applications

(*b*). The impulse strength for repeated applications

(*c*). Sixty-cycle strength

Impulse strength for limited applications means single applications of voltage each setting raised in five-per-cent steps to breakdown. Table I and figure 2 give the results of these tests for positive and negative full, chopped, and steep-front waves for a total of 28 shells.

Impulse strength for repeated applications means as many as 100 applications of voltage each setting raised in approximately ten-per-cent steps to breakdown. Table II and figure 3 give the results for positive, full, and steep-front waves, and for negative full, chopped, and steep-front waves for a total of 13 shells.

For the 60-cycle tests a voltage of about 80 per cent of the expected failure was applied for one minute. A rest period of one minute intervened. The voltage was raised in five-per-cent increments to breakdown. This procedure was repeated for five shells. On one shell the voltage was rapidly applied to breakdown. The results are summarized in table III.

The breakdown of a single test specimen varies as much as ten-per-cent and more from the average, as shown in tables I, II, and III. For limited applications the variation on the average is five to ten per cent. The test data for repeated applications are more consistent, the average variation not exceeding five per cent. Some of the 60-cycle breakdown values depart substantially from the average.

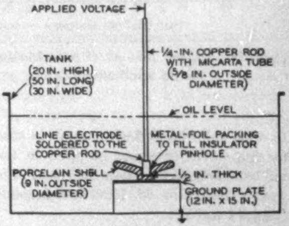
APPLIED VOLTAGE
TANK (20 IN. HIGH) (50 IN. LONG) (30 IN. WIDE)
¼-IN. COPPER ROD WITH MICARTA TUBE (⅝ IN. OUTSIDE DIAMETER)
OIL LEVEL
LINE ELECTRODE SOLDERED TO THE COPPER ROD
METAL-FOIL PACKING TO FILL INSULATOR PINHOLE
PORCELAIN SHELL (9 IN. OUTSIDE DIAMETER)
½ IN. THICK
GROUND PLATE (12 IN. x 15 IN.)

Figure 1. Arrangements of porcelain shells for test

Porcelain has a characteristic similar

Table I. Impulse Strength of Porcelain Shells for Limited Applications

Porcelain Number	Test*	Number of Impulses	Kilovolts Held	Kilovolts Breakdown	Time to Breakdown (Microseconds)	Kilovolts Per Microsecond	Kilovolts Average Breakdown	Average Time to Breakdown (Microseconds)
1	Positive full wave 1½x48 microseconds	6	160	168	3.0		154	2.9
3		1		137	4.0			
12		6	153	158	3.3			
5	Positive wave chopped at 2–3 microseconds	4	154	163	2.2		156	2.64
6		4	159	158	2.3			
7		3	148	159	2.5			
8		1		140	3.3			
9		6	171	179	2.5			
10		1		136	2.7			
11		4	141	153	3.0			
13	Positive wave-steep fronts	2	198	213	1.4	152		0.74
14		3	256	265	0.62	427		
15		1		279	0.59	473		
16		1		277	0.57	487		
17		1		279	0.29	967		
18		1		330	0.3	957		
24	Negative full wave 1½x48 microseconds	11	199	205	2.3		219	2.9
25		5	185	194	2.3			
26		11	232	241	3.0			
27		10	225	235	3.0			
28	Negative wave chopped at 2 microseconds	7	201	209	2.0		209	2.3
29		8	210	209	2.5			
30		8	205					
19	Negative wave—steep fronts	1		339	0.2	1,690		0.37
20		1		330	0.19	1,735		
21		1		282	0.5	563		
22		1		298	0.53	563		
23		1		307				

* In these tests the full wave was 1½x48 microseconds which for these tests is equivalent in effect to either the 1½x40-microsecond (AIEE) or the 1x50-microsecond (IEC) waves.

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1. For all numbered references, see list at end of paper.

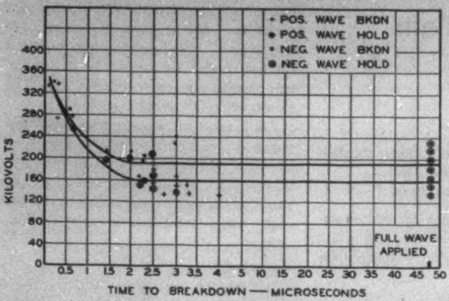


Figure 2. Impulse strength of porcelain for limited applications

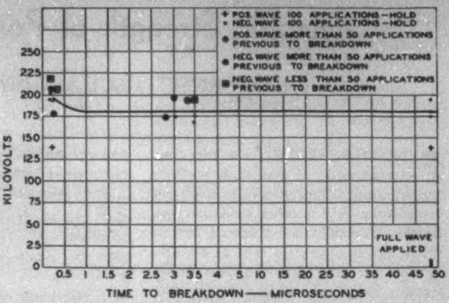


Figure 3. Impulse strength of porcelain for repeated applications

to other solid insulation materials in that for full waves or waves chopped on the tail breakdown occurs near the crest of the wave, from two to four microseconds (tables I and II).

For the majority of impulse tests the puncture of the porcelain (figure 5) was from the edge of the line electrode where the greater stress appears. In relatively fewer cases failure occurred near the center. The failure is in the nature of a fused path the size of an ordinary pin or greater through which the current discharged. When testing on the front of the wave, due to the higher setting of the impulse generator, holes were blown in the porcelain by the explosive action of the heavier current. Breakdown on 60 cycles was at the corner of the electrode.

From figures 2 and 3, a polarity effect is apparent for the specimen and electrode arrangement employed. For impulses, two microseconds and longer the negative voltage is about 20 per cent greater than the positive. At the very short time, for single applications, the polarity effect practically disappears.

The voltage-time characteristic for limited applications (figure 2) is a constant voltage for waves two microseconds and longer. For shorter durations, an upturn of the curve takes place with an increase in the voltage of nearly 100 per cent at 0.3 to 0.2 microsecond. These very short impulses are chopped on a front which rises at approximately 1,000 kv per microsecond (tables I and II).

For repeated applications (figure 3) the voltage-time characteristic is a constant voltage with the indication of an upturn on approaching durations less than one microsecond. The voltage strength for repeated impulses is about 90 per cent of that for limited applications for two microseconds and greater. These tests show that at 0.2 microsecond the single application breakdown is 70 per cent greater than for repeated applications.

The impulse ratio (impulse voltage divided by 60-cycle one-minute hold) of the flat part of the voltage-time characteristic for limited applications (figure 2) is respectively 1.47 and 1.75 for positive and negative waves. The average for the two polarities is 1.61. For repeated applications (figure 3) the impulse ratio is 1.28 for the positive and 1.65 for the negative waves. The average is 1.47.

Porcelain Tubes—Test Results

Tests were made on one-inch-thick porcelain. The specimens consisted of porcelain tubes, one-inch inside diameter through which a metal tube fitted snugly. Midway on the outside of the tube, a tinfoil band and flange similar to a bushing arrangement comprised the ground. Voltage was applied to the metal tube. The tests were made in transformer oil at 26 degrees centigrade. Tests at higher temperature did not show appreciable change in breakdown. The strength of several samples to a 1½x40-microsecond positive wave for limited applications averaged 237 kv and the one-minute 60-cycle hold, 146 kv (crest). Thus the impulse ratio is 1.62. This value compares closely with the corresponding

Table II. Impulse Strength of Porcelain Shells for Repeated Applications

Porcelain Number	Test*	Kilovolts	Number of Impulses	Kilovolts	Number of Impulses	Kilovolts	Number of Impulses	Kilovolts	Number of Impulses	Total Impulses	Kilovolts per Microsecond	Kilovolts Breakdown	Time to Breakdown (Microseconds)
37	Positive full wave 1½x48 microseconds	118	50	126	50	140	100	154	52	253		154	
41	Positive wave—steep fronts			132	100	139	100	176	54	255	765	176	0.23
31	Negative full wave 1½x48 microseconds			178	100	196	54			155		196	
32				175	50					51		175	
35				175	100	195	12			113		195	
33	Negative wave chopped at 2–3 microseconds			175	100	195	2			103		195	3.5
34				175	100	195	68			169		195	
36				175	51					52		175	2.8
44				171	100	195	88			189		195	3.5
38	Negative wave—steep fronts	150	100	165	100	193	99			300	918	193	0.23
39		150	100	165	100	193	200	218	22	423	800	218	0.18
42				176	100	202	90			191	1,040	202	0.2
43				176	100	200	109			210	1,000	200	0.2

* In these tests the full wave was 1½x48 microseconds which for these tests is equivalent in effect to either the 1½x40-microsecond (AIEE) or the 1x50-micro second (IEC) waves.

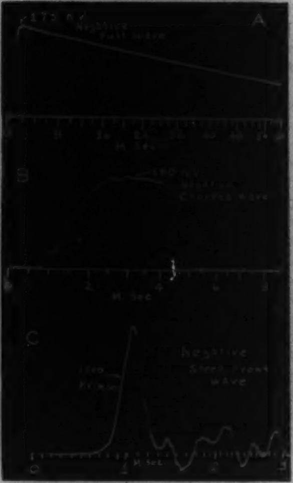


Figure 4. Typical oscillograms of test applied

A—Full wave
B—Wave chopped on tail
C—Steep-front wave

average impulse ratio for the tests on porcelain shells. From these and similar tests the relation between voltage strength and porcelain thickness is a straight line on log-log co-ordinates with a slope of 0.5.

Steep-Front Tests on Suspension-Insulator Strings

Strings of 3, 5, and 14 standard suspension insulators were flashed over with negative waves on a 3,000 to 4,000 kv per microsecond front. Thirty impulses in succession were applied to each string. The 14-unit string was last to be tested. Four insulators in this string already had been subjected to 30 impulses, so that these four units received a total of 60 impulses. The test data are summarized in table IV.

Table III. Sixty-Cycle Strength of Porcelain Shells

Porcelain Number	Test	Maximum One-Minute Hold Voltage: Kilovolts (Crest)	Maximum One-Minute Hold Voltage: Average	Breakdown Voltage: Kilovolts (Crest)	Breakdown Voltage: Average	Time Hold (Seconds)
45	60-cycle voltage applied one minute—one minute rest between steps	93.5	111	99	116	10
46		110.0		116		40
47		140.0		147		30
48		99.0		104		50
49		111.0		116		40
50	60-cycle voltage rapidly applied (approximately 10–15 seconds)			159		

The five-insulator assembly was in addition subjected to combined steep-front and high-current flashovers (figure 6). This test simulates a lightning stroke discharge.[4] Table V summarizes the test data.

No sign of damage to the insulators was apparent from either the steep front or combined tests. These results are particularly significant as these tests approach or simulate in severity the stresses to which insulators may be subjected on lines as the result of direct strokes. On the basis of uniform distribution of the voltage, the insulators of the three-unit assembly were stressed the highest (table IV). Each insulator withstood repeated impulses of 330 kv with approximately 0.25-microsecond duration. The porcelain thickness of the insulators, between cap and pin, is approximately $^{13}/_{16}$ of an inch; the cap and pin are assembled to the shell with cement.

Suspension Insulators Tested to Breakdown in Oil

Impulse tests to breakdown were applied to the insulators previously tested on steep fronts. Each insulator was immersed in transformer oil similar to the arrangement of figure 1, voltage being applied to the pin. The voltage was raised by steps to breakdown. Table VI summarizes the data.

Tests were made on 60 cycles. The results are given in table VII. In these as in the other tests reported in the paper good transformer oil (30 to 35 kv, standard cup test) was used, except for the three 60-cycle tests (table VII) where due to contamination the strength of the oil was 17 kv. Even then no apparent difference is noted in the puncture strength of the insulators.

The impulse tests indicate that the negative full-wave strength is somewhat higher than the positive full-wave but the data are insufficient to establish definitely the amount. The average breakdown for the positive and negative full waves is 265 kv. The average 60-cycle one-minute

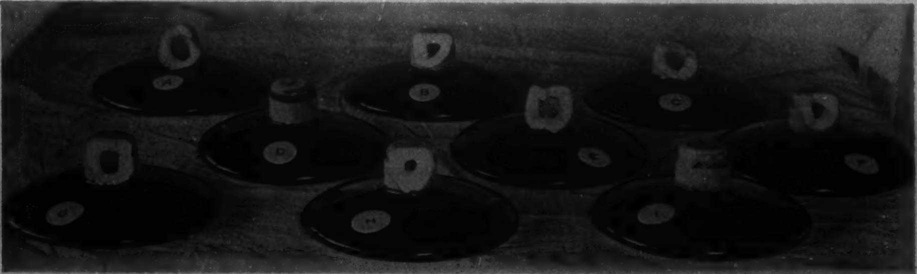


Figure 5. Typical breakdown of porcelain shells

Repeated applications:
A—Negative full wave
B—Negative wave chopped on tail
C—Negative steep-front wave
D—Positive full wave
E—Positive steep front

Limited applications:
F—Positive steep front
G—Negative steep front
H—Negative wave chopped on tail
I—Positive wave chopped on tail

Table IV. Steep-Front Impulse Tests on Suspension Insulator Strings, Negative Polarity

Insulator Units* in String	Number of Impulses	Voltage Applied		Comment
		Kilovolts	Kilovolts per Microsecond	
3	30	1,000	4,000	No apparent damage
5	30	1,300	3,000 to 4,000	No apparent damage
14	30	2,100	3,500**	No apparent damage

* Standard insulators, 10-inch diameter, 5¾-inch spacing.

** Rise of front. Flashover in 1.5 to 1.6 microseconds.

Table V. Combined High-Voltage and Current Impulse Tests on Five-Unit Insulator String*

Number of Tests	Voltage Applied		Current		Comment
	Kilovolts	Kilovolts per Microsecond	Amperes	Total Duration (Microseconds)	
4	1,300	3,000 to 4,000	40,000	70	No apparent damage

* These tests made on same five-insulator string in table IV. Polarity of voltage and current negative.

hold strength is 163 kv (crest). Therefore the impulse ratio is 1.62, a figure close in agreement with the results for the porcelain shells and tubes.

From these tests the voltage-time characteristic (table VI) rises at 0.2 microsecond approximately 50 per cent above the 2- to 40-microsecond value. This amount in the upturn is not so great as the tests of the porcelain shells (figure 2) show due possibly to the difference in the electrode arrangements and in the specimens, and in particular to the relatively larger number of impulses that were applied to the suspension insulators previous to (table IV) and during the breakdown tests (table VI).

Figure 6. Combined high-voltage and current impulse test on five-unit insulator string

Comparison of Porcelain Data

As a basis of comparison the data for the one-half-inch shells have been plotted in figure 7 as impulse-ratio/time curves. The corresponding impulse ratios for the one-inch tubes and the suspension insulators from 2 to 40 microseconds are essentially the same as in curve *A* (limited applications).

The 30 flashovers in air of the suspension insulator assemblies indicate that a stress was sustained by the insulator units which corresponds to an impulse ratio of 2.0 at 0.25 microsecond. This value compares to 1.7 of curve *B* where, however, the number of tests applied to the one-half-inch shells in oil is greater. Following the flashover tests, the limited tests on the suspension insulators in oil (table VI) give an impulse ratio of 2.0 at 0.28 microsecond and of 2.4 at 0.17 microsecond. Although the test data on the suspension insulators are not on the same basis as the curves of figure 7 and therefore cannot be directly compared, the data well substantiate the impulse-ratio characteristic of porcelain as given by these curves.

In a recent investigation for the comparison of impulse tests sponsored by the International Electrotechnical Commission, tests[5] are reported by Allibone on thin (0.15-inch) porcelain cups with an electrode arrangement simulating a rather uniform field. The tests were made in oil at room temperature. Repeated impulses were applied. Essentially the same voltage was obtained for positive and negative waves. From this investigation the impulse ratio for 1-, 5-, and 50-microsecond waves are respectively 1.55, 1.48, and 1.46. These values are in close agreement with the corresponding data in curve *B* of figure 7.

Sixty-cycle tests in oil of suspension insulators have been a subject of considerable investigation, for the condition of the oil affects the puncture voltage. Insulators tested in oil of abnormally low resistivity show some 30-per-cent increase in puncture voltage over the tests made in normal transformer oil, due apparently to the grading effect that low-resistivity oil has on the concentrated field at the metal parts. Rebora[6] has investigated the effect of the oil on the puncture voltage of standard suspension insulators. His data for the tests in normal transformer oil are in substantially good agreement with ours (table VII) both in regard to the relative values and in the nature of the breakdown. In these tests (table VII) where normal transformer oil was used no substantial grading at the cap edge or at the pin could have been present since streamer formation could be observed as the test voltage was increased to the puncture value. The concentrated stress is indicated also from the frequent occurrence of failure through the porcelain shell from the edge of the cap to the pin. The flashover data of the insulators (in air) point out the possibility that for air the corona and streamers from the cap and pin are of such a nature as to have a grading effect. By virtue of this grading effect a higher stress would be sustained by the insulator (tables IV and VI).

Table VI. Impulse Strength of Suspension Insulators Tested in Transformer Oil

Insulator Unit	Test	Number of Impulses	Kilovolts Breakdown	Microseconds
A	Positive full wave	15	260	1½x40
B		7	230	
C		17	265	
D	Negative full wave	20	290	1½x40
E	Negative wave–steep fronts	16	320	0.28
F		3	395	0.17

Comments: Oil temperature 24 degrees centigrade. Dielectric strength of oil 30 kv in standard cup. 0.1-inch gap, one-inch disks. Time to breakdown of *A*, *B*, *C*, and *D*, three to eight microseconds. Failure of *A*, *B*, *D*, and *E* from cap edge to pin. Failure of *C* and *F* inside cap to pin.

While the dielectric strength of porcelain is affected by and varies with the test specimen, the electrode arrangement, the method of test, and other factors, the data presented in this paper and elsewhere establish that the curves of figure 7 are representative of the voltage-time characteristic of porcelain.

Apparatus in Service

The voltage-time characteristic of porcelain is apparent also from the performance of apparatus in service. As an illustration, suspension line insulators will be considered since this apparatus is frequently stressed in service from traveling waves and direct strokes. Moreover, line insulators are well standardized and their flashover characteristics fully established.[7]

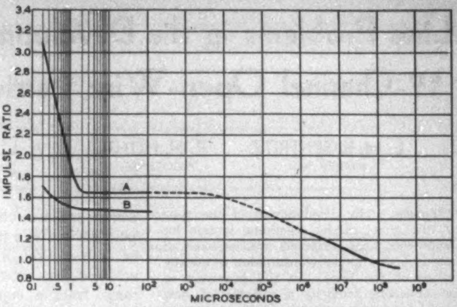
The porcelain thickness between cap and pin for standard insulators is about 0.80 inch. For the 1.5x40 microsecond wave flashover the average stress per insulator is from 100 to 90 kv for insulator strings of 5 to 16 elements. The average stress per insulator for a two-microsecond impulse is approximately 130 kv. These stresses are for equal voltage distribution over the insulator string and require multiplying by a factor greater than unity for departure, from uniform distribution. It is conceivable also that in the process of flashover stresses exceeding these average values would appear across the individual insulators for the very short time in which the flashover occurs. All considered, the good performance of modern line insulators to traveling waves is naturally expected.

Experience shows that even direct strokes seldom, if ever, puncture the porcelain in modern suspension insulators. Consider the probable stress of the porcelain from the various records of direct strokes to the line. An oscillogram of a direct stroke to a 220-kv line[8] (16-insulator assembly) indicates a rate of rise of 1,500 to 2,000 kv per microsecond, the voltage reaching a crest of 3,000 kv. Other records and analyses[9,10,11] indicate that rates of rise up to 5,000 kv per microsecond possibly are attained.

Considering 3,000 kv per microsecond as or near the upper limit for the steepness of the front of lightning strokes, from table IV and other published data[4,12,13], the average stress and its duration per element for a 16-insulator string would be approximately 200 kv and 1.2 microsecond. For a 5-insulator string the average stress and duration are 280 kv and 0.5 microsecond and for a 3-insulator string, 330 kv and 0.25 microsecond. The ability of insulators to withstand these stresses is demonstrated from the tests reported in this paper (tables IV and V) and in a previous investigation.[4]

The good performance of line insulators even when subject to direct strokes is quite understandable from fundamental considerations of the dielectric strength of porcelain. Furthermore, this analysis indicates that the steepness of the front of direct strokes possibly is not so great as assumed in the past.

Figure 7. Impulse ratio-time characteristics of porcelain for limited applications (A) and for repeated applications (B)



Conclusions

1. The voltage-time characteristic of porcelain for limited applications is a constant voltage down to two microseconds and rises with shorter impulses nearly doubling at 0.2 microsecond.

2. For many repeated applications, the voltage-time characteristic is practically constant with relatively smaller upturn at the shorter impulses.

3. The impulse ratio on the flat part of the characteristic is 1.60 for limited applications and approximately 1.45 for repeated applications.

4. These inherent characteristics of porcelain are apparent also from the good performance of line and other apparatus subjected in service to traveling waves and direct strokes.

5. The characteristics of porcelain compared with its good performance in service indicate that the steepness of strokes on lines possibly does not or seldom exceeds 3,000 to 5,000 kv per microsecond.

Table VII. Sixty-Cycle Strength of Suspension Insulators Tested in Transformer Oil

Insulator Unit**	Test	Maximum One-Minute Hold Voltage (Kilovolts Crest)	Breakdown Voltage Kilovolts Crest	Breakdown Voltage Time Hold (Seconds)	Remarks*
G	60-cycle voltage applied one minute. One minute rest period between steps	132	145	55	Oil temperature 25 degrees centigrade. Oil strength 35 kv
H		161	166	35	
I		168	175	45	Oil temperature 20 degrees centigrade. Oil strength 17 kv
J		168	175	30	
K		161	168	10	
L		175	182	50	Oil temperature 20 degrees centigrade. Oil strength 31 kv
M		168	175	15	
N		161	168	45	
O		168	175	55	
		Average = 163			

* Dielectric strength of oil determined in standard cup. 0.1-inch gap between one-inch disks.

** Failure of *G, H, I, J, L, N,* and *O* from cap edge to pin; of *K* and *M* from inside cap to pin.

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Discussion

Victor Siegfried (Worcester Polytechnic Institute, Worcester, Mass.): This paper is of interest in that it fills in a gap in the information on dielectric strengths of materials where no great amount of data exists. The behavior of porcelain is shown to be similar to that of other solid dielectrics in the volt-time characteristics, and in the difference in characteristics on repeated application as compared with a limited number of voltage applications.

In obtaining their data, the authors have used porcelain shells without hardware. I am wondering what difference might be expected when a cap is on the units, giving a more even distribution of stress on the inside corner next to the pin. It might be expected at first guess that the characteristics would be similar to those found, but at different values for the actual breakdown voltage, thus giving a higher actual voltage which the unit could withstand. If there is a tangible difference, it will affect the extension of these data to other cases where the actual porcelain insulator with line hardware is used.

In general, this paper shows the ability of the modern insulator to stand up under the severest stresses imposed by line conditions; in fact, the authors very significantly conclude that the proved ability of the insulators to take strokes in service indicates a maximum steepness of wave of 3,000 to 5,000 kv per microsecond. This shows us that the laboratories cannot go wrong in speeding up the wave fronts to such a value when attempting to duplicate the worst type of impulse that natural lightning is likely to produce.

P. L. Bellaschi and **M. L. Manning**: The tests on complete porcelain units to which Mr. Siegfried refers are given in tables IV to VII inclusive. One of the objects of the paper was to establish the volt-time characteristic of porcelain. Accordingly, plain shells, completely assembled in insulator units, tubes, etc., were tested. In these tests, different electrode arrangements were used for the various specimens. The average results of such tests are given in figure 7, which is the representative volt-time curve of porcelain.

We are in full agreement with Mr. Siegfried in that the tests verify the good performance of porcelain expected and found in service.

Line Problems in the Development of the 12-Channel Open-Wire Carrier System

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Synopsis: The development of the type *J* 12-channel carrier telephone system for open-wire lines required an increase of nearly 5 to 1 in the transmission frequency range of the lines. In the provision of suitable line facilities a number of new problems were encountered with respect to attenuation, noise and cross talk. Methods for meeting these problems and the results obtained are described.

A NEW carrier telephone system for open-wire telephone lines has been described recently.[1] This system increases the number of two-way telephone circuits which can be obtained on a single pair of wires from the previous maximum of 4 to a total of 16. This has been achieved by extending the frequency range from a maximum of about 30 kilocycles to more than 140 kilocycles. The exploitation of this new range of frequencies on open wire has involved the solution of a number of interesting problems, among which are these:

1. Not only does the attenuation of an open-wire line under ordinary weather conditions rise substantially with frequency but extremely large increases in attenuation occur at the higher frequencies when ice forms on the wires.[2,3] In spite of these effects a high degree of stability of transmission has been secured on all channels by the provision of automatic control of repeater gain and equalization.

2. New cross-talk problems created by the extension of the frequency range have been solved by the development of transposition designs with numbers of transpositions not greatly in excess of those employed for the lower-frequency systems. Problems have also arisen in controlling the cross talk around the repeaters and in reducing the effect of impedance departures between the line circuits and the equipment.

Frequency Allocations

The type *J* system operates on circuits on which type *C* carrier systems were already operating in the frequency range up to about 30 kilocycles. To provide enough frequency separation between the two systems the lower frequency limit of the *J* system was set at 36 kilocycles; the necessary frequency space for 12 channels in each direction set the upper limit at about 140 kilocycles. This range is split into two parts, one used for transmission in one direction and the other for the opposite direction. Figure 1 illustrates the relation of the frequency bands occupied by the type *J* and type *C* systems and the voice-frequency channel. Different "staggered" locations of the frequency bands are to be employed in order to simplify cross-talk problems.

Filters are used for separation of the type *J* from the type *C* and lower-frequency facilities on the same pair of wires. This separation is done by means of a combination of high- and low-pass filters which split apart the frequency ranges above and below the band between 30 and 36 kilocycles. To simplify the design of these filters, the low-frequency group of the type *J* system is transmitted in the same direction as the high-frequency group of the type *C* system. This arrangement of transmitting certain frequencies in a particular direction is generally used throughout the telephone plant in order to avoid serious cross-talk difficulties. Accordingly with few exceptions west to east transmission or south to north transmission takes place in the same frequency bands throughout the country and similarly, east to west or north to south transmission employs the same frequency bands. These are indicated in figure 1.

Line Attenuation

An open-wire pair affords the lowest-loss transmission medium of any conductor employed in the telephone plant. It is, however, peculiarly subject to the effect of weather, which may cause large and often rapid changes in the attenuation. In consequence, some form of gain regulation is required.

Even for carrier systems operating up to 30 kilocycles, manual regulation is inadequate for the longer systems and automatic devices have been provided for

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[1] For all numbered references, see list at end of paper.

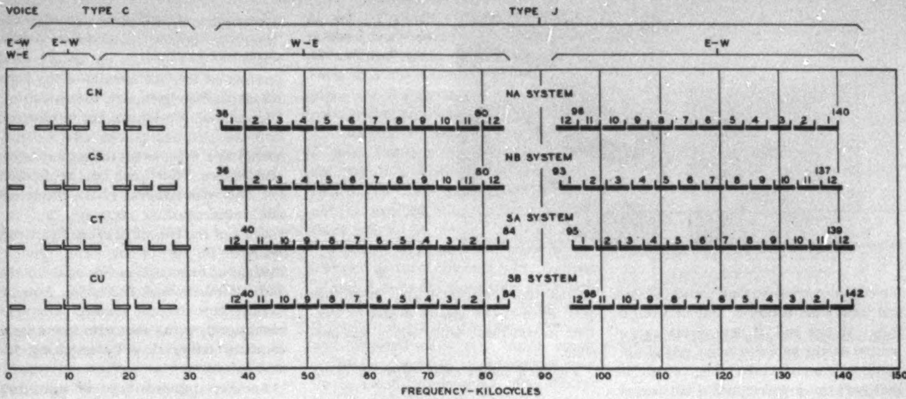


Figure 1. Frequency allocation

Note: E-W also implies transmission N-S and W-E implies S-N

most systems over 500 miles in length. The attenuation changes caused by changes in resistance of the wire with temperature or by changes in the shunt losses when insulators become wet are much larger at the higher frequencies of the *J* system, and therefore, an automatic regulating scheme is required. Tests were made on open-wire circuits to determine more precisely the characteristics needed for such a regulator. During sleet storms, when wires are covered with ice, the increases in attenuation are far beyond any caused by rain. Figure 2 shows increases which may be caused by ice as compared with the normal dry- and wet-weather values.

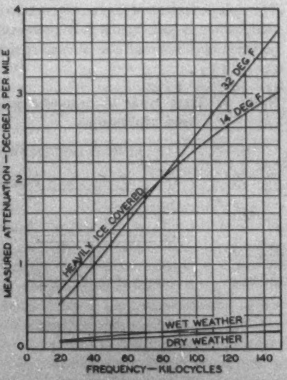


Figure 2. Attenuation variation with weather

Eight-inch spacing, 165-mil copper wire

The deposits on the wire may be actual ice, or in some cases wet snow or frost adhering to the wire. Figure 3 shows an example of such deposits. Theory shows that the increase in attenuation is caused by energy losses in the ice itself and that leakage across the insulators is usually a negligible factor.

An extensive survey of the effects of ice has been carried on at various points throughout the country during the past four years and a large amount of information has been accumulated. These tests have shown that the shape of the attenuation-frequency characteristic differs considerably for different ice formations and even if the ice deposit remains the same for a time, the attenuation-frequency characteristic may vary with temperature as in figure 2. The two upper curves of the figure were measured at different times during the same storm. There was no apparent change in deposit between the two measurements. This change in shape of the characteristic, of course, makes the regulation problem more difficult. In spite of the extreme severity of ice effects in certain regions it is expected that satisfactory reliability will be obtained on type *J* systems by placing the repeaters sufficiently close together.

Regulation Problem

In the first type *J* systems the regulator actuated by a single pilot frequency in each direction compensates for the attenuation changes caused by temperature and wet weather.

The required varieties of attenuation slopes with ice on the wires could not be provided by a simple regulator. Hence provision is to be made in later designs for a regulator with variable slope controlled by two pilot frequencies which is expected to be satisfactory in areas subjected to sleet conditions. The regulating range will also be increased so that a completely automatic control of gain up to about 75 decibels will be available.

It was found that during periods when ice coated the wires the circuit noise measured at the end of a repeater section usually decreased as the attenuation increased. This is important because otherwise the extra increase in the repeater gain to take care of the higher attenuation at such times would make the noise excessive. The study of ice conditions throughout the country which has been carried on and is still continuing will be useful in laying out repeater stations along some of the routes which eventually will be candidates for the application of type *J* systems.

Open-Wire Cross Talk

The cross-talk problem on open-wire lines is one of the most important. Cross talk is controlled by transpositions which are introduced into the various pairs in accordance with a predetermined design. The creation of the necessary designs requires consideration both of the complex theory of transpositions and measurements on lines constructed by practical methods.

However, the design of transposition systems is considerably simplified by the use of different frequencies for the two directions of transmission. The only cross talk between systems which is

Figure 3. Ice on wires and insulators near Amarillo, Tex.

directly important is that known as far-end cross talk, which is that between a talker at one end of one circuit and a listener at the opposite or far end of another. Near-end cross talk, which is that between a talker and a listener at the same or near ends of two circuits, becomes a source of interference between circuits only when portions of it appear as far-end cross talk because of reflections at points of impedance irregularity in the circuits.

Because of the high cost of a transposition design to keep both near-end and far-end cross talk down to small values, only small reflections are permitted where open-wire and cable meet, or where circuits are terminated in equipment. A number of the difficulties which had to be overcome to attain small reflections are discussed later in the paper. With this control the transposition designer can concentrate most of his attention on far-end cross talk, the near-end cross-talk requirements are relaxed, and a cheaper transposition arrangement can be used.

What can happen when reflection occurs may be seen by comparison of the near-end and far-end cross-talk curves in figure 4. The similarity in the shapes of the two curves, and particularly the fact that the peaks occur at the same frequencies, show that what appears to be far-end cross talk is in this case mostly reflected near-end cross talk. It is for pair combinations such as this one, where the near-end cross talk is much larger than the far-end, that the closest control of reflection effects is required. With the values of reflection realized in the *J* system, reflected cross talk will ordinarily be unimportant.

To obtain satisfactory cross-talk conditions at the higher frequencies some changes in line construction are necessary. To use type *J* carrier systems on existing open-wire routes, methods were devised for modifying the line construction in as economical a manner as possible. For new lines, such as the new part of the fourth transcontinental line[5] advantage was taken of the greater degree of freedom in structural design which was possible.

Figure 5 shows three types of open-wire pole head configuration suitable for *J* system operation. The left-hand diagram shows a method of reconstructing part of one of the older types of open-wire lines built with 12-inch spacing between wires of the pairs and with the "alternate arm" transposition system which was developed for the use of type *C* systems on the side circuits of the horizontal phantom groups on alternate arms. This method is a flexible one in that one or more phantom groups may be converted at a time, as on the second crossarm shown. For such an application not only was removal of the phantoms and retransposition necessary, but the spacing of the two wires of each pair was reduced to six inches. This general method of construction was used for the Dallas-Houston and Dallas-San Antonio lines,[6] except that the six-inch pairs were constructed with new wire on a new crossarm rather than by respacing 12-inch pairs.

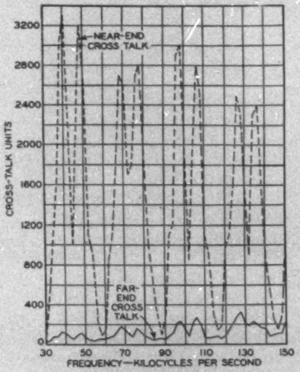


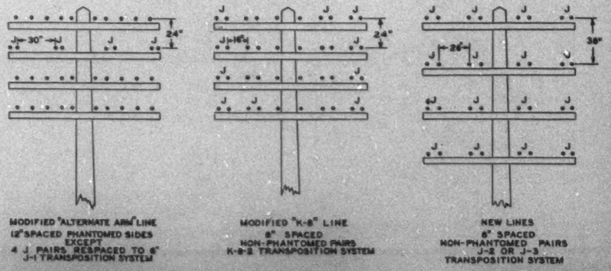
Figure 4. Near-end and far-end cross talk—J-3 transposition system

Pairs 3/4–9/10

Another common type of open-wire pole-head configuration, the middle diagram of figure 5, is that made up of eight-inch-spaced nonphantomed pairs transposed in accordance with the *K*-8 transposition system on an eight-span base. Through design studies supplemented with field experiments it was found that such a line could be converted for *J* systems much more cheaply than an alternate-arm line. If *J* systems are restricted to the pairs on the outer ends of the crossarms, with two inner pairs, about one or two transposition changes in each pair per mile are enough. This scheme was followed in reconstructing the line between Charlotte, N. C., and West Palm Beach, Fla.

For new lines yet to be built, a greater degree of latitude in structural design is naturally possible. The right-hand diagram of figure 5 shows an open-wire pole-head configuration designed to allow *J* systems to be operated on all of the pairs. The unique feature of this configuration is that, while 8-inch spacing is preserved between the wires of the various pairs,

Figure 5. Three types of open-wire pole head configuration



the adjacent nonpole pairs on a crossarm are separated by 26 inches and the crossarms by 36 inches. The reduction in coupling made possible by this increased spacing keeps the cross talk for any combination of pairs down to a suitable value with transposition arrangements not necessarily more complicated than those employed for the other configurations. This type of construction was used for the new parts of the fourth transcontinental line.

Figure 6 shows a comparison of the number of transpositions used in a typical section of open-wire line for various types of circuits from voice-frequency phantomed circuits to nonphantomed circuits intended for *J* system operation. From the original arrangement where there was one transposition point in every ten spans, about one-fourth mile, the number of transpositions for *J* carrier operation has been increased so that for the *J*-3 design, which was used for the new wires on the fourth transcontinental line, there are four transpositions in each eight-span interval and every pole is a potential transposition point.

It may be seen from figure 8, however, that the number of transpositions required in pairs for *J* carrier operation is not necessarily larger than the number employed in systems intended for *C* carrier operation with a top frequency of 30 kilocycles. The superiority of the *J* system transposition arrangements as compared with those designed for *C* system operation results from the choice of specific arrangements which best limit the systematic effects for frequencies in the *J* system range.

Typical far-end cross talk measured between eight-inch-spaced pairs 11–12 and 19–20 on a new *J*-3 line and on a reconstructed *K*-8-2 line is shown by figure 7. The superiority of the new line with its fewer wires, greater wire separations, better transposition system, and smaller irregularities is evident.

Absorption Effects

The attenuation of an open-wire pair may be quite unsatisfactory if there are what are known as absorption effects, caused by induction into surrounding circuits such that energy is absorbed in particular frequency bands and the attenuation of the pair increased. These effects, which depend on the transposition arrangements in the circuits, may cause objectionable transmission distortion at critical frequencies unless the transpositions are planned to avoid them. The same arrangements necessary to control cross talk between *J* systems will automatically eliminate absorption effects with one exception. If only part of the pairs on a line are designated and transposed for *J* systems and the remaining pairs are not so transposed, absorption in a *J* pair can be caused by a nearby non-*J* pair. Consequently, consideration of the cross-talk relations at *J* frequencies between all of the pairs on the line cannot be avoided even though some of them will not be used for *J* systems.

Figure 8 illustrates the effect of absorption on three different pairs. Curves *A* and *B* show the absorption measured over the type *J* frequency range on a line of the alternate-arm type. Curve *A* was obtained on a side circuit transposed for operation at frequencies only up to about 10 kilocycles. The absorption at frequencies above this becomes very large. Curve *B* shows the absorption present on one of the *C* carrier side circuits on the same line transposed for operation up to 30 kilocycles. Curve *C* shows how absorption disappears on a nonphantomed pair specially transposed for type *J* operation. If this pair were measured at much higher frequencies, similar absorption "bumps" would be found, perhaps at frequencies of 200–300 kilocycles or higher.

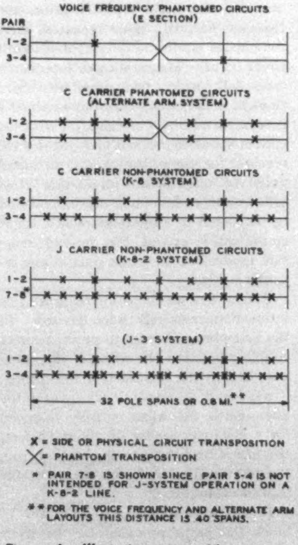

VOICE FREQUENCY PHANTOMED CIRCUITS
(E SECTION)
PAIR
1-2
3-4
C CARRIER PHANTOMED CIRCUITS
(ALTERNATE ARM. SYSTEM)
1-2
3-4
C CARRIER NON-PHANTOMED CIRCUITS
(K-8 SYSTEM)
1-2
3-4
J CARRIER NON-PHANTOMED CIRCUITS
(K-8-2 SYSTEM)
1-2
7-8*
(J-3 SYSTEM)
1-2
3-4
32 POLE SPANS OR 0.8 MI.**
X = SIDE OR PHYSICAL CIRCUIT TRANSPOSITION
╳ = PHANTOM TRANSPOSITION
* PAIR 7-8 IS SHOWN SINCE PAIR 3-4 IS NOT INTENDED FOR J-SYSTEM OPERATION ON A K-8-2 LINE.
** FOR THE VOICE FREQUENCY AND ALTERNATE ARM LAYOUTS THIS DISTANCE IS 40 SPANS.

Figure 6. Illustrative transposition arrangements

Since absorption effects depend on the systematic addition of cross-talk currents along a line, a continuous succession of identical transposition sections tends toward greater absorption while a random succession of different kinds of transposition sections of different lengths will reduce it. The Dallas-Longview *J* system is operating on an alternate-arm side circuit, transposed for *C* carrier operation and without any modifications to adapt it for the higher frequencies. Because of the fortunately irregular succession of different transposition sections found here, it was possible to select, after tests, a pair with no serious absorption.

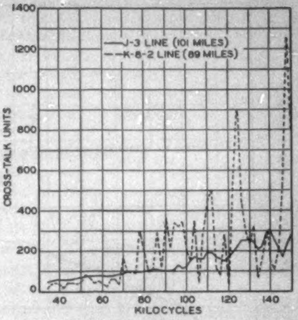


Figure 7. Far-end cross talk between eight-inch-spaced pairs 11/12 and 19/20

Construction Irregularities

With the new transposition designs, the systematic cross talk resulting from the transposition arrangements has been reduced in nearly every case so far that the remaining cross talk is controlled principally by construction irregularities. An important source of irregularity is the difference in sags of the various wires in each span of the line, particularly sag differences between the two wires of each pair. Another potentially important source of irregularity is the variation in the spacings between successive transposition poles. It is relatively easy to make this factor unimportant as compared with sag differences.

The large amount by which the cross talk can be reduced by careful methods of construction coupled with the highly developed systematic transposition patterns is illustrated by the fact that between certain pairs the cross talk in a 75-mile repeater section is reduced to a value which would be produced by a capacitance unbalance between them of less than two micromicrofarads, which is about the same in magnitude as the capacitance between wires of a foot of the

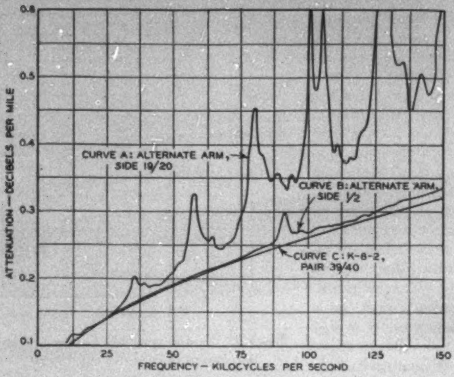


Figure 8. Attenuation of open-wire pairs of different types

Curves *A* and *B*—Side 19/20 and 1/2, respectively, on alternate-arm line, 104-mil, 12-inch, 56.7 miles, 90 degrees Fahrenheit, at Mascoutah, Ill.

Curve *A* is transposed for voice frequencies

Curve *B* is transposed for carrier operation up to 30 kilocycles

Curve *C* is pair 39/40 on K-8-2 line, 104-mil, 8-inch, 50 degrees Fahrenheit and CS insulation between Denmark, S. C., and Rincon, Ga., transposed for carrier operation up to 140 kilocycles

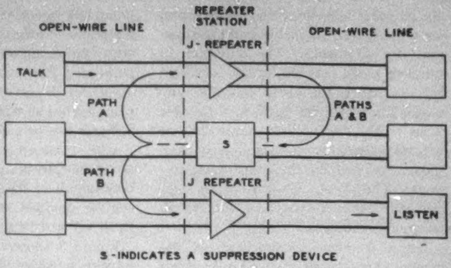


Figure 9. (above). Interaction cross talk at a *J* repeater station

open-wire pair. This large cross-talk reduction is in spite of the fact that at 140 kilocycles the phase change along an open-wire circuit is about 7 degrees in a single span, the shortest distance between any two transpositions, and about 28 degrees for the more common four-span interval.

Interaction Cross Talk at Repeater Points

Another type of problem was introduced by what is known as interaction cross talk. This is the cross talk which occurs from one side to the other of a *J* repeater station. Figure 9 illustrates two paths which it may take. Path *A* shows the cross talk from a system to itself which may cause transmission distortion or repeater singing while path *B* is the path of cross talk between different circuits. The essential feature of this interaction cross talk is that, as figure 9 shows, the cross-talk path at a repeater station passes through the *J* repeater and hence the cross talk is amplified by the repeater gain.

The new problems of controlling this cross talk were the result of larger magnitudes of cross talk at the higher frequencies, the larger repeater gains, and the fact that with more repeaters there were more points on a system where it could occur. Magnitudes of interaction cross talk which had previously been thought of as inconsequential assumed a new importance. For instance, with the gain of about 75 decibels proposed for the repeater for use in sleet areas, an initial value of unamplified interaction cross talk as low as 0.25 cross-talk unit would be magnified to 1,400 units, which might considerably exceed the far-end cross talk existing at the same time in one repeater section.

Several new methods for reducing this interaction cross talk were devised. In the first place, in order to prevent direct coupling between the wires of the open-wire line on the two sides of the station, it was found necessary to cut a gap in the line. With the wires entirely removed for a distance usually of about 80 feet, the line is brought into the station from the two terminal poles by means of the lead-in cables.

It was also seen to be necessary to block the paths provided by the wires of the telephone line itself. For this purpose, cross-talk suppression filters were designed and built to be installed in all of the non-*J* circuits on the line. These give losses of the order of 70 decibels at 140 kilocycles not only in the metallic transmission circuits but also in other circuits, made up of various combinations of the line wires, which may conduct cross-talk currents through the stations.

In addition to the cross-talk suppression filters and in order to provide an extra margin of safety against interaction cross-talk currents which might find their way through the repeater station by stray paths, longitudinal choke coils have been connected at the pole heads between the open wires and the lead-in cables. These coils do not disturb ordinary transmission but add high impedance in the longitudinal circuits.

These measures for controlling interaction cross talk have been found to be adequate so far as the telephone line is concerned. At an occasional *J* repeater station, however, located on a right-of-way occupied by several pole lines, there is found another pole line paralleling the telephone line with a separation sometimes as little as two to five feet between the nearest wires of the two lines. Such wires provide other interaction cross-talk paths past the repeater station and impair the effectiveness of suppression measures installed in the line on which the *J* system is operated. The by-passing effects of such a foreign line can be controlled by cross-talk suppression devices similar to those used in the telephone line wires.

Figure 10 shows a comparison of the interaction cross talk measured at a *J* repeater station before any suppression measures were installed, the other wires of the line being continuous at the station location, with the corresponding interaction cross talk when the line was run through the suppression devices in the station. The values shown would be amplified by the gain of the *J* repeater on the disturbed circuit before they reached the listener. The effect of the by-passing foreign line is illustrated by the difference between the middle and bottom curves, the bottom curve showing the measured cross talk when the by-passing line was cut to simulate the effect of suppression measures in it.

Staggered Systems

It would not be possible with the open-wire line configurations now in use to design transposition arrangements that

Table I

Transposition System	Wire Spacing (Inches)	Noise (Decibels)*	Repeater Spacing in Miles—128-Mil Wire
Alternate arm	12	+10	67
K-8-2	8	+ 5	82
J-1	6	− 2	103

* Above reference noise, 10^{-12} watt at 1,000 cycles.

would permit the operation of identical *J* systems on all pairs. For this reason four types of *J* systems with different channel carrier-frequency allocations will be provided in the future. The frequency assignments for these systems are shown in figure 1.

The "staggering" advantage, or effective cross-talk reduction between systems, is effected because (1) the inversion or displacement of channels in the different systems with respect to each other makes the cross talk unintelligible, and (2) the reduction of the overlap between channels results in less energy being transferred between them by cross talk. The net benefits of "staggering" obtained by the allocations shown in figure 1 range from about 6 to 16 decibels.

The most effective pair assignments for the four types of *J* systems can best be obtained from actual cross-talk data on the particular sections of line involved. The "staggering" advantages obtained are sufficient so that the highest remaining cross talk will usually occur between the like *J* systems operating on nonadjacent pairs.

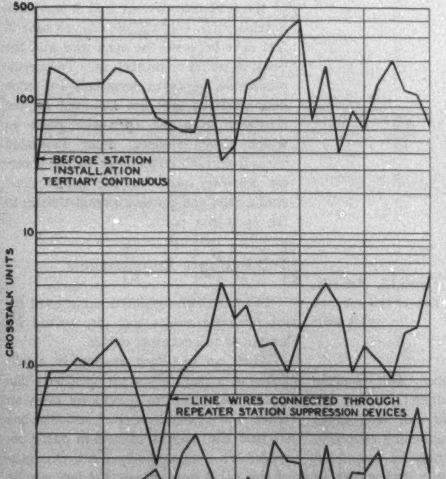


Figure 10. Unamplified interaction cross talk between two J circuits at an auxiliary repeater station

Noise

Observed external sources of noise in *J* systems are atmospheric static, dust storms, radio stations, power-line carrier, and power-supply systems.

Of these possible sources the more important will usually be atmospheric static which will be greatest during the summer months. In regions where dust storms occur, their effects are expected to exceed that of atmospheric static but will be more likely to occur during the winter and early spring.

Table I shows values of noise at 140 kilocycles, caused by atmospheric static, found at the open-wire line terminals of one repeater section; the values are those which it is expected will be exceeded during one per cent of the summer season extending from May to September. If the repeater spacings shown were used, the total static noise in the top channel at the end of a circuit with 20 repeaters would be 20 decibels above reference noise at the −9-decibel level. However, other factors such as ice may require the use of shorter spacings.

Line Impedance

As mentioned previously in the discussion of cross talk, it is important that the line impedances be matched closely and large irregularities be avoided. Because of the different wire sizes and pair spacings, a wide range of open-wire line impedances may be encountered. Novel construction arrangements and the development of new lead-in circuits have made it possible to secure a reflection coefficient of about five per cent at the junction between the open-wire pair and the toll entrance and office equipment at the highest transmitted frequency.

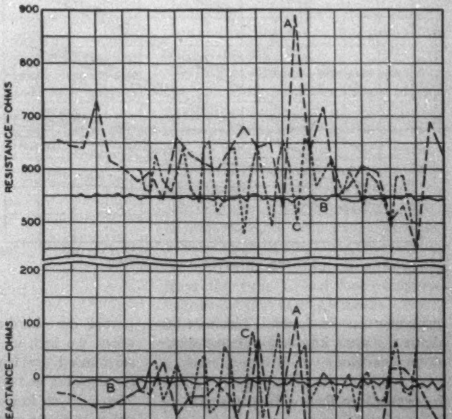
The transposition arrangement and wire spacing of a pair affect the smoothness of its impedance because they affect the reactions between circuits which

Figure 11. Impedances of open-wire pairs of different types

A—104-mil, 12-inch-spaced, side 17/18 of an alternate-arm line

B—165-mil, 8-inch-spaced, pair 17/18 of new J-3 line

C—128-mil, 8-inch-spaced, pair 31/32 of K-8-2 line with miscellaneous lengths of tree wire, etc.



cause absorption effects. The marked improvement which can be obtained by proper design is illustrated by comparison of curves *A* and *B* of figure 11. Curve *A* shows the impedance of a 12-inch-spaced side circuit on an alternate-arm line. This particular circuit was one intended for use at frequencies not above ten kilocycles. In striking contrast curve *B* shows the comparatively smooth impedance of an eight-inch-spaced nonphantomed pair on a new line transposed in accordance with the *J*-3 system.

"Tree" wire, a special line wire with abrasion-resistant insulation, has been used on open-wire lines for many years in places where the lines were exposed to tree branches. During line tests in Florida, another use for tree wire was found where the open-wire line, along a causeway or bridge, is subject to fouling by fishing tackle. Curve *C* of figure 12 shows what a half-mile or so of this tree wire, supplemented by several sections of 165-mil wire at railroad and power-line crossings, can do to the impedance of a 128-mil pair. To reduce the irregularities a new type of insulated line wire of smaller diameter and with thinner insulation was developed. This wire has about the same impedance characteristic as the line wire.

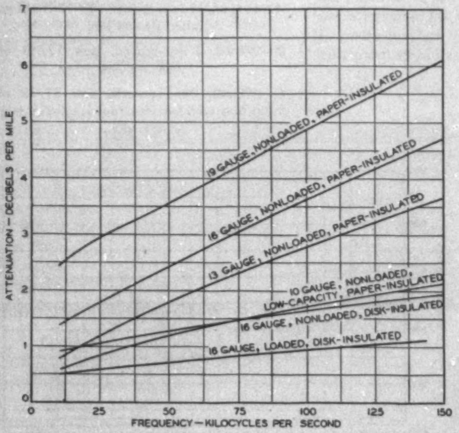


Figure 12. Attenuation of toll entrance cable pairs

Intermediate Cable Treatment

When open-wire lines have to be placed underground to pass through towns or to cross natural barriers such as rivers which cannot be spanned economically with open wire, cable is used. In the past, the circuits in such cables were frequently loaded to reduce their attenuation and to match the impedance of the open-wire circuits in order to avoid reflection effects and degradation of voice-frequency repeater balance. To load paper-insulated cable pairs for frequencies up to 150 kilocycles would require exceedingly short loading spacing, of the order of 200 feet, which would be expensive and in many cases impractical with existing manhole locations. An alternative, the use of a transformer to match the open-wire and cable impedances, was rejected as it was found impractical to design a transformer which would be adequate over the entire frequency range.

To overcome these difficulties, a new low-capacitance type of cable was developed which could be loaded to match the open-wire impedance with coil spacings about the same as those previously used. Loading coils of different sizes were developed to provide for loading to the different impedances of the open-wire circuits.

The new cable employs 16-gauge conductors in a spiral-four arrangement, supported by hard-rubber disk spacers about 0.6 inch in diameter. These are surrounded by copper and iron tapes for shielding and strengthening purposes. The units so formed may be assembled either in single units in a lead sheath as for lead-in purposes, or in multiple units, up to a maximum of seven for full-sized cable, within the same lead sheath. For duct runs or submarine cables, the multiple assembly is usually employed, and, in the latter case, with outside armoring and jute protection. If the submarine span is more than about 600 feet, intermediate submarine loading is employed.

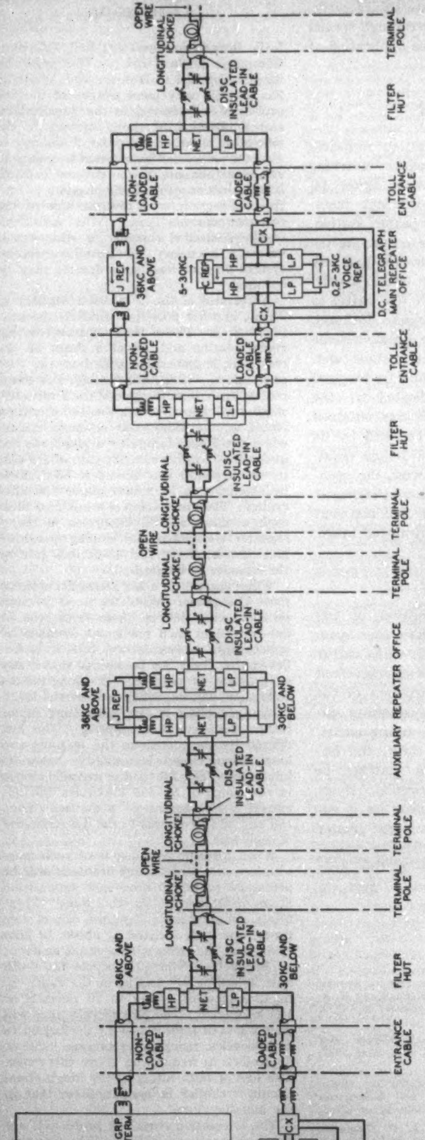
As an alternative, it sometimes happens that where a long intermediate cable is involved, an auxiliary type *J* repeater station can be placed conveniently at one end of this cable. In this case, the filter hut described in the discussion of toll entrance arrangements in the next section may be used at the end of the cable opposite the repeater station and the cable treated as a toll entrance cable for the auxiliary office. A further alternative is to provide filter huts at the two ends of a nonloaded intermediate cable. However, if the cable is short, the new disk-insulated cable with loading is to be preferred.

Previous practice at the ends of open-wire lines has been to use paired bridle wire with weatherproof insulation and usually of smaller gauge than the line wire to connect the open-wire pairs to cable terminals mounted on the pole. Other pairs of bridle wire were connected between the open wires and protectors. Because of the much more severe reflection requirements at the higher frequencies of the type *J* system, these arrangements were no longer satisfactory. The characteristic impedance of bridle wire is roughly one-fifth of that of the open-wire circuit and it has been necessary to avoid the use of even several feet of it between the open-wire and the cable terminal or protectors. To accomplish this, separate terminals for each disk-insulated unit are mounted on the crossarm near the open-wire pairs to which they connect. Four insulated wires from each terminal go by the shortest feasible route to the longitudinal choke coils and protectors and thence to the open-wire pairs.

Toll Entrance Arrangements

The new disk-insulated cable used for intermediate cables was also suited for lead-in or toll entrance cables.

When an auxiliary station is established at a point along an open-wire line where there has not previously been an office, it is usually located close to the line so that the lengths of lead-in cable required are comparatively short. Lengths of this cable up to about 175 feet can be loaded to open-wire impedances with adjustable loading units in the repeater station. For longer lead-in cables up to 300 feet, supplementary loading may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LOADED CABLE
ENTRANCE CABLE
36KC AND ABOVE
30KC AND BELOW
NET
FILTER HUT
DISC INSULATED LEAD-IN CABLE
LONGITUDINAL CHOKE
TERMINAL POLE
OPEN WIRE
TERMINAL POLE
J REP
36KC AND ABOVE
30KC AND BELOW
AUXILIARY REPEATER OFFICE
TERMINAL POLE
OPEN WIRE
TERMINAL POLE
FILTER HUT
TOLL ENTRANCE CABLE
J REP
36KC AND ABOVE
5-30KC
C REP
0.2-3KC VOICE REP
D.C. TELEGRAPH MAIN REPEATER OFFICE
TOLL ENTRANCE CABLE
FILTER HUT
TERMINAL POLE
OPEN WIRE

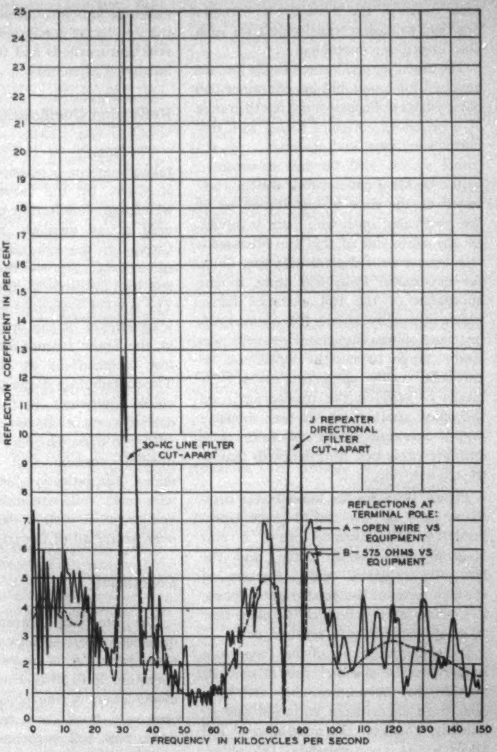

Figure 14 (above). Reflection coefficient at junction between open-wire and toll entrance equipment

be mounted directly on the pole at the cable terminals.

When an auxiliary repeater station is not close to the open-wire line, or at main repeater stations which are frequently in towns and separated from the open-wire line by greater lengths of toll entrance cable, it is still possible to use the loaded disk-insulated cable. Because of the cost of this cable and its loading, however, it has sometimes been found more economical to build a hut near the open-wire terminal pole and to separate the type *J* from the type *C* and lower-frequency facilities at that point by means of filters. The connection from the open-wire line to the hut is provided by what is usually a short length of loaded disk-insulated cable. From that point, the type *J* frequencies are led into the toll office over nonloaded paper-insulated pairs while the *C* and lower-frequency facilities are brought in over the existing pairs, usually loaded. By thus limiting the frequencies transmitted over the nonloaded

Figure 13. Toll entrance arrangements at *J* terminal and repeater offices

cable pairs to the *J* range, it becomes practical to design transformers for suitable impedance matching.

The line filter sets located in the hut are designed for a nominal impedance of 560 ohms which is a compromise for the range of impedances normally found with different wire sizes and spacings. An accurate match with the line is obtained with a building-out network which is adjusted at the time of installation to fit the particular open-wire pair involved. On the office side of this line filter set a transformer provides for stepping down the impedance from 560 ohms to the impedance of the toll entrance cable, which is usually about 125 ohms. Adjustment of this impedance over the necessary range to match impedances of particular cable pairs is provided by means of taps on the transformer. At the office another transformer similarly tapped is employed to match the toll-entrance-cable pair impedance to that of the office wiring.

Figure 12 shows the losses of the commonly used 19-, 16-, and 13-gauge paper-insulated toll entrance cable, a new 10-gauge low-capacity cable, and the new disk-insulated cable. Because of the high losses of the smaller-gauge pairs, it is sometimes economical to place new 10-gauge cable to save repeater costs.

For the office wiring of the *J* system a rubber-covered shielded pair is used to provide the desired flexibility and freedom from capacitance variation due to humidity changes. Its impedance at 140 kilocycles is approximately 125 ohms. The repeater and terminal high-frequency impedances are designed to match this impedance very closely.

Figure 13 illustrates the arrangement of the toll entrance equipment involved in matching the line impedance to that of the equipment with a minimum of reflection. The terminal is illustrated to the left. The high-frequency line passes to the line filter set which is here shown as located in a filter hut. There it is joined by the type *C* and lower-frequency circuits and passes through the lead-in cable and protective arrangements on the terminal pole.

Proceeding toward the right in the figure, the arrangement at an auxiliary repeater station is shown. In this case the type *J* frequencies are amplified in the repeater, but the type *C* and lower frequencies are by-passed through filters which suppress longitudinal and metallic transmission above 30 kilocycles. At the right is shown a combined type *J* and type *C* main repeater office.

Satisfactory cross talk between pairs in entrance and intermediate cables carrying *J* systems is effected through special selection methods and the application of balancing capacitors.

Reflection Coefficients

The success of the various measures taken to ensure good impedance matching is shown by the curves of figure 14, which are of reflection coefficients measured at an auxiliary repeater station. Curve *A*, the solid line, gives the coefficient between the open-wire pair and the lead-in cable at the terminal pole. The smaller variations are due partly to irregularities of the open-wire line and, at the lower frequencies, partly to the test terminations at the distant end. The contribution of the cable loading and office equipment is indicated by the dash-line curve *B*, which was obtained with the open-wire line replaced by its nominal impedance, a 575-ohm resistance. The reflection between the open-wire and toll entrance and repeater equipment is well under five per cent over nearly all of the transmitted range.

Conclusion

The successful transmission of frequencies up to 140 kilocycles over open-wire pairs as compared with earlier operation up to 30 kilocycles has involved modification of the construction of the open-wire lines, new transposition designs, new toll entrance arrangements, including new types of cable, the improvement of impedance matches in various parts of the circuits, closer repeater spacings, and, where ice is encountered, provision for much greater gain margins with more flexible regulation. By the first part of this year about 60,000 channel-miles were in service over type *J* systems.

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4. Open-Wire Cross Talk, A. G. Chapman. *Bell System Technical Journal*, volume 13, January and April 1934, pages 19–58, 195–238.

5. Transcontinental Telephone Lines, J. J. Pilliod. Electrical Engineering, volume 57, October 1938, pages 418–19 and 423.

6. Some Applications of the Type J Carrier System, L. C. Starbird and J. D. Mathis. AIEE Transactions, volume 58, 1939, pages 666–74 (December section).

Discussion

L. L. Burns (Southwestern Bell Telephone Company, Dallas, Tex.): The paper by Messrs. Ilgenfritz, Hunter, and Whitman has given a very good picture of the line problems encountered in the development and application of the *J* system to the telephone plant. It may be of interest to note that it has not been found necessary to use cross-talk suppression devices in paralleling wires on other leads in order to control interaction cross talk at any of the repeater points in Texas. With the advent of the 75-decibel repeater or whenever it becomes necessary to install a second system on any lead such devices may be required.

At several of the *J* repeater stations in Texas, another pole line parallels the telephone line. These lines by-pass the repeater station and act as a shunt on the cross-talk suppression applied to the telephone lines. If the loss through this shunt path is lower than the gain of the *J* repeater, singing will occur. Such was the condition found at the Edgewood repeater station when the Dallas-Longview system was cut in service. In this case the gain of the east to west repeater was limited to 33 decibels by singing at a frequency above 150 kilocycles. The installation of a low-pass filter with a cutoff at 150 kilocycles in the *J* repeater eliminated the singing condition and permitted the full 45-decibel gain of the repeater to be used.

When circuits on other lines offer a shunt path at repeater points the need for suppression measures in these lines will be determined in each particular instance by appropriate measurements, but it is believed that there is a possibility that if any suppression is required, the longitudinal coils alone will be sufficient since the longitudinal coupling is the controlling factor rather than metallic coupling. The loss offered by these coils to the metallic and longitudinal circuit is negligible below 35 kilocycles. The loss to the metallic circuit in the range of 35–150 kilocycles will not exceed a few tenths of a decibel. Each coil will add two ohms to the d-c resistance of each wire.

When metallic coupling is of such magnitude as to become important, it will be necessary to install cross-talk suppression filters in the circuits on other lines. These filters as at present designed are of two types, one with a cutoff at about 12 kilocycles and the other with a cutoff at about 35 kilocycles. The 12-kilocycle filter will offer a loss of 0.5 decibel in the range up to 12 kilocycles, rising to 70 decibels at 140 kilocycles. The 35-kilocycle filter will offer a loss of from 0.2 to 0.7 decibel up to 30 kilocycles, rising to an average value of 55 decibels at frequencies above this range. The loss of both filters in the longitudinal circuit is similar in magnitude to that in the metallic circuit.

The interaction cross-talk problem is not confined to repeater points. Where an east terminal and a west terminal are installed in the same office, the coupling between the outputs of the two terminals may be enough to cause intelligible cross talk. A part of this coupling may be direct between the two circuits and a part may be due to coupling through a third line. This third line might be a telephone cable, a power line, or signal line which parallels both open-wire leads or cables for a short distance. This condition existed in the Dallas office. It was found in this particular case that the attenuation offered by the relatively long paper-insulated toll entrance cables to frequencies in the *J* range together with the shielding effect of these cables was sufficient to prevent appreciable cross talk. Longitudinal choke coils may be installed in each circuit in one of the toll entrance cables, if necessary to minimize cross talk of this type. Such coils were installed in one of the Dallas toll entrance cables but subsequently removed when it was found that they were not required.

R. W. Linney (Southwestern Bell Telephone Company, Oklahoma City, Okla.): The authors have given an interesting description of the problems encountered, the methods of solving them, and the results obtained by their application in connection with the installation of the 12-channel carrier telephone systems to open-wire lines. There is a large number of open-wire lines on which the *J* carrier systems will be installed in the future. The toll fundamental plans will indicate the most probable lines for development with the new carrier systems. On existing lines some of the modifications necessary for the application of the *J* carrier systems may be made more economically over a period of years before the time the system is required. These lines are constantly being altered on account of ordinary deteriorations and additions and are occasionally rerouted on account of obstructions.

The following is a list of the ordinary construction activities encountered in maintaining an open-wire line which can be directed in a systematic program to effect a reduction in the costs of modifying a line for *J* carrier operation:

1. *Pole Replacements.* The poles replaced should be located to fit in with the proposed transposition layout. This involves preparation of the transposition schemes in advance.

2. *Long-Span Installations.* Long spans introduce serious problems to *J* carrier facilities. Consideration should be given to the location of transpositions and to the spacing of wires to meet the requirements of *J* carriers.

3. *Intermediate and Entrance Cable Installations.* Proposed intermediate and entrance cables with their complicated design should be compared with open-wire reroutes, keeping in mind that the cables at best offer transmission inferior to open wire.

4. *New Wire Stringing Projects.* In placing or replacing wire on a line, consideration should be given to locating it in such a position and spacing it so as to be suitable for carrier operation.

5. *Major Crossarm Replacement Projects.* Ordinarily crossarm replacements are scattered so that a wire respacing job could not be associated. However, in certain cases where a phantom is not in use, it would be practicable to respace the wires at the time a major crossarm replacement job is carried out.

6. *Rerouting Sections of Line.* Where sections of lines are relocated to clear highways and other obstructions, the new construction should be carried out to provide for the ultimate carrier requirements for the section involved. The new route should avoid paralleling other overhead lines especially near proposed *J* repeater stations to reduce interaction cross talk. Power-line carriers, power-supply lines, and radio stations at close proximity should also be avoided as these systems are a source of noise in *J* circuits.

A program including some of the items mentioned above has been in effect in connection with applying *C* and *D* carrier systems and material savings have been obtained. The more rigid design requirements of the outside plant associated with the application of the higher-frequency carriers offers an even better field of application for such a program.

R. M. Carpenter (Southwestern Bell Telephone Company, Houston, Tex.): The paper very comprehensively presents the many varied and technical problems encountered in the application of high-frequency telephone channels to open-wire telephone lines. Several factors not heretofore offering any appreciable hindrances to commercial transmission must now be given minute study and consideration. Just how well the Bell Telephone Laboratories have done the job of overcoming these obstacles is illustrated by the fact that several *J* carrier systems are now rendering high-grade telephone service in several parts of the nation under many varied conditions. The authors of this paper played the major role in the development of this carrier and its application to different types of open-wire structures, and deserve much credit for doing an excellent work.

We in Texas are very much interested in the economies offered by the 12-channel open-wire carrier system as a means of providing much of the additional toll facilities required to keep pace with the increasing usage of long-distance telephone service. This carrier system is particularly adapted to providing many additional miles of high-frequency communication channels from the large number of existing long-haul toll circuits in the Texas area. Most of the major toll lines in Texas consist of open-wire structures and there are relatively great distances between the larger toll points. An extended use of such systems seems feasible in Texas not only because of the above features, but also for the reason that the conditions contributing to line problems are not as severe as in most parts of the nation.

Firstly, deposits of ice on wires in Texas, as a whole, are not a frequent occurrence. The picture of the ice on wires and insulators near Amarillo, Tex., does not lend any strength to this statement, but, those of you who are acquainted with the storm-loading areas, know that only a small portion of Texas is in the heavy-loading area, where, for pole-line-design purposes, heavy ice may be expected at certain intervals. A somewhat larger section lies in the medium-loading area where a lighter coating of ice may be had at rare intervals, but by far the greater portion is in the light-loading area where no ice is considered for design purposes. In deference to the picture, it should be said that ice will form more frequently on the wires in the colder Panhandle section of Texas, but, in the rest of the state, in the heavy and medium areas, sleet will not be a factor more than once or twice each year, and, in the light-loading area is a rarity. Therefore, deposits of ice which greatly attenuate the high frequencies cannot be considered a major problem in most parts of Texas.

Secondly, the toll lines in Texas will have shorter lengths of entrance and intermediate cables in their make-up than will those in more densely populated sections of the country. In the 265-mile line between Dallas and Houston, there is not more than 11 miles of cable, and, in the 290-mile Dallas-San Antonio line, the cable mileage is proportionately low. Inasmuch as cable inflicts a severe penalty on the higher frequencies of this open-wire carrier system and requires costly loading as well as special types of conductors in some instances, it is readily seen that the less cable there is in a toll line, the greater economy there is in placing *J* carrier systems on the line.

Thirdly, external sources of noise will not be as great as in some sections of the country. Dust storms occur frequently in the Panhandle and other parts of west Texas, and, in recent years, some of these have been blown eastward into central and east Texas, three to five times each year, but, in general, the portion of the state having most of the major toll lines is affected little or none by dust storms. The relatively low density of population in Texas serves to keep to a minimum such external sources of noise as radio stations, power-line carrier, and power-line supply systems.

Texas has been fortunate in securing most of the early pioneering installations of *J* carrier systems, and, in view of the above favorable conditions, will, no doubt, find it economical and practicable to make an extended further use of this type of communication facility.

Some Applications of the Type J Carrier System

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MEMBER AIEE

J. D. MATHIS
ASSOCIATE AIEE

Synopsis: Previous papers before the AIEE describe the development of a 12-channel type *J* carrier system. This paper discusses some of the practical problems encountered in extending the circuit capacity of existing open-wire lines by the use of this carrier system.

The first systems of this type were placed in commercial operation late in 1938. One of these systems is discussed in detail from the standpoint of obtaining satisfactory operation with the most economical arrangement of new and existing facilities.

A 12-CHANNEL carrier telephone system for open-wire lines was described before the AIEE early this year,[1] and a discussion of the requirements of line facilities for its operation has been presented.[2] Since the first three systems to be placed in commercial operation are located in Texas, it seems appropriate to present to the South West District meeting the major problems arising from the practical application of this type system on existing open-wire plant.

In 1935 it became apparent that existing open-wire facilities on some of the major toll lines in Texas would soon be exhausted. In the case of the Dallas-Houston, Dallas-San Antonio, and Dallas-Longview lines, current growth and requirements for the future indicated that comprehensive relief would have to be provided ultimately. This probably will be a toll cable. At the time, however, the development of the open-wire 12-channel *J* carrier system made available an arrangement for obtaining a large number of additional circuits over the existing lines which would provide for the immediate requirements and also permit postponement of more costly relief measures for a number of years.

The type *J* system operates in a frequency range above that of the three-channel type *C* carrier system and can be superposed on the same conductors with the type *C*, thereby providing a total of 16 circuits from one pair of conductors. However, conductors suitable for type *C* carrier operation are not necessarily satisfactory for the operation of the new system.

The three lines under consideration were practically of the same construction, being 12-inch phantomed lines originally built for voice-frequency circuits only and later modified for the application of type *C* carrier systems. Over lines of this type, it is practicable to operate a single type *J* system without any material change in the line wire because no crosstalk considerations are involved, although it is necessary to select by transmission measurement pairs which are free from absorption effects. Where more than one system is required a transposition arrangement has been designed for use with line conductors of a nonphantomed pair spaced 6 inches apart and 30 inches between conductors of horizontally adjacent pairs. This design can be used either for new wire or for existing wire retransposed, and can be applied without regard to the existing phantomed transposition design, thereby permitting respacing and retransposing any portion of the existing wire, a phantom group at a time if desired.

Figure 1. Typical pole with extension fixture

Advance Engineering

With these operating limitations a review of the circuit requirements established a plan to place a *J* carrier system on one of the phantom groups of the Dallas-Longview line during 1938. This system would not only provide sufficient circuits to meet the additional requirements but would furnish sufficient spare circuits to release one phantom group of 12-inch wire for respacing and retransposing. This plan was not applicable to the Dallas-Houston and Dallas-San Antonio lines since circuit relief was required for the 1937 business, and the *J* carrier system would not be available until 1938. These lines each consisted of five crossarms of 104-mil wire over the greater portion of their length. An inspection showed that, although the poles

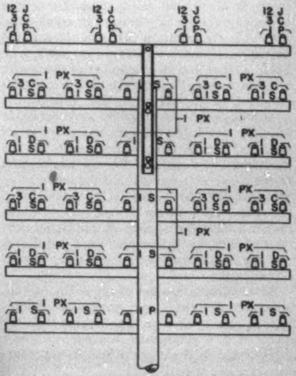

Figure 2. Pole head diagram showing circuit capacity of the Dallas-Houston and Dallas-San Antonio lines

P—Physical circuit
PX—Phantom circuit
S—Side circuit
C—*C* carrier circuit
D—*D* carrier circuit
J—*J* carrier circuit

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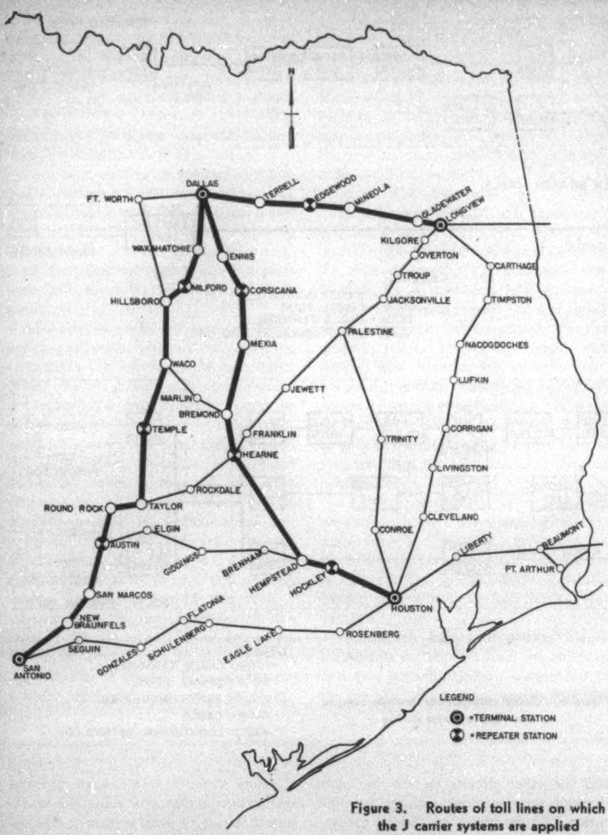
1. For all numbered references, see list at end of paper.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DALLAS
TERRELL
EDGEWOOD
MINEOLA
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TIMPSON
WAXAHATCHIE
ENNIS
MILFORD
CORSICANA
HILLSBORO
PALESTINE
NACOGDOCHES
MEXIA
WACO
LUFKIN
JEWETT
MARLIN
BREMOND
TEMPLE
FRANKLIN
CORRIGAN
TRINITY
HEARNE
LIVINGSTON
ROCKDALE
ROUND ROCK
TAYLOR
CLEVELAND
ELGIN
CONROE
AUSTIN
GIDDINGS
BRENHAM
HEMPSTEAD
HOCKLEY
LIBERTY
BEAUMONT
PT. ARTHUR
SAN MARCOS
HOUSTON
FLATONIA
NEW BRAUNFELS
SCHULENBERG
EAGLE LAKE
ROSENBERG
SEGUIN
GONZALES
SAN ANTONIO
LEGEND
=TERMINAL STATION
=REPEATER STATION

Figure 3. Routes of toll lines on which the J carrier systems are applied

were of sufficient strength to support additional crossarms, it would be difficult to maintain the necessary wire clearance with an additional crossarm below the existing wire and also that new wire so placed would be susceptible to interference from possible breaks in the wire above.

The solution of this problem was the addition of a crossarm two feet above the others on a simple extension fixture. This fixture shown in figure 1 consists of a four-inch steel H beam fastened to the pole by the through bolts which also support the two upper crossarms. By placing four pairs of six-inch-spaced conductors on the new crossarm and by using four type *C* carrier systems, 16 additional circuits were obtained to furnish the circuit relief for 1937 and, in addition to the immediate relief, four suitable *J* carrier paths were provided of which one on each line was needed in 1938. Figure 2 is a typical pole head and shows how the ultimate circuit capacity of this open-wire plant has been expanded from 69 to 133 circuits by the addition of one crossarm and eight conductors. The use of 128-mil wire instead of 104-mil wire provides greater strength and the particular location reduces the probability of interrupting 16 circuits by a single wire break or other physical interference.

The program of placing three type *J* carrier systems in service in Texas during 1938 was established. Figure 3 is a map of a portion of the state showing the routes of the lines and the principal cities along the routes. Since the length and attenuation of each of these lines are such that the carrier systems cannot operate without intermediate amplification, it was necessary that the number and locations of repeater stations be determined.

Typical System

The layout of a particular system is largely controlled by available repeater gain, existing entrance cables, line attenuation under normal and adverse weather conditions, location and availability of existing telephone buildings, and availability of commercial power for new buildings. Line attenuation is increased greatly by deposits of ice on the wire during sleet conditions. Although data are available regarding the frequency of large deposits of ice, there is very little information as to the amounts or frequency of occurrence of small deposits. Under normal wet-weather conditions the maximum attenuation of six-inch-spaced 128-mil facilities at 140 kilocycles is 0.35 decibel per mile.

On the Dallas-San Antonio line the facilities available consisted of 286 miles of six-inch-spaced 128-mil copper wire and 42,000 feet of 16-gauge nonloaded paper-insulated cable. Using repeaters having a maximum amplification of 45 decibels in

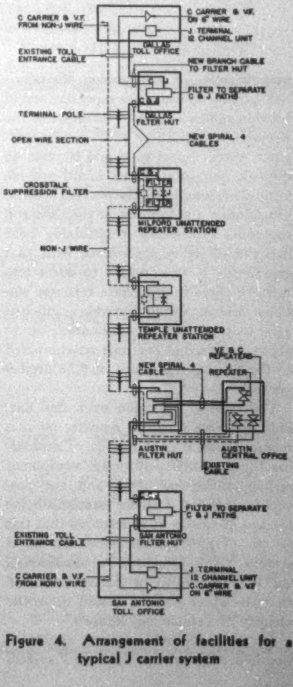
C CARRIER & V.F. FROM NON-J WIRE
C CARRIER & V.F. ON 6" WIRE
J TERMINAL 12 CHANNEL UNIT
DALLAS TOLL OFFICE
EXISTING TOLL ENTRANCE CABLE
NEW BRANCH CABLE TO FILTER HUT
C
J
FILTER TO SEPARATE C & J PATHS
C & J
TERMINAL POLE
DALLAS FILTER HUT
OPEN WIRE SECTION
NEW SPIRAL 4 CABLES
C & J
FILTER
C & J
FILTER
CROSSTALK SUPPRESSION FILTER
MILFORD UNATTENDED REPEATER STATION
NON-J WIRE
TEMPLE UNATTENDED REPEATER STATION
VF & C REPEATERS
NEW SPIRAL 4 CABLE
J REPEATER
AUSTIN FILTER HUT
AUSTIN CENTRAL OFFICE
EXISTING CABLE
FILTER TO SEPARATE C & J PATHS
EXISTING TOLL ENTRANCE CABLE
SAN ANTONIO FILTER HUT
C CARRIER & V.F. FROM NON-J WIRE
J TERMINAL 12 CHANNEL UNIT
C CARRIER & V.F ON 6" WIRE
SAN ANTONIO TOLL OFFICE

Figure 4. Arrangement of facilities for a typical J carrier system

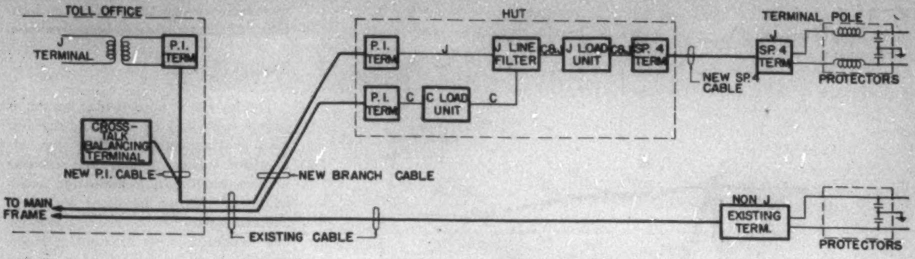
TOLL OFFICE
J TERMINAL
P.I. TERM
CROSS-TALK BALANCING TERMINAL
NEW P.I. CABLE
TO MAIN FRAME
HUT
P.I. TERM
J
J LINE FILTER
C&J
J LOAD UNIT
C&J
SP. 4 TERM
P.I. TERM
C
C LOAD UNIT
C
NEW SP. 4 CABLE
TERMINAL POLE
J
SP. 4 TERM
PROTECTORS
NEW BRANCH CABLE
EXISTING CABLE
NON J
EXISTING TERM.
PROTECTORS
LEGEND:
P.I. = PAPER INSULATED
SP. 4 = SPIRAL FOUR
TERM. = CABLE TERMINAL
= LONGITUDINAL RETARD COIL

Figure 5. Circuit connections through Dallas filter hut from open wire to terminal equipment at central office

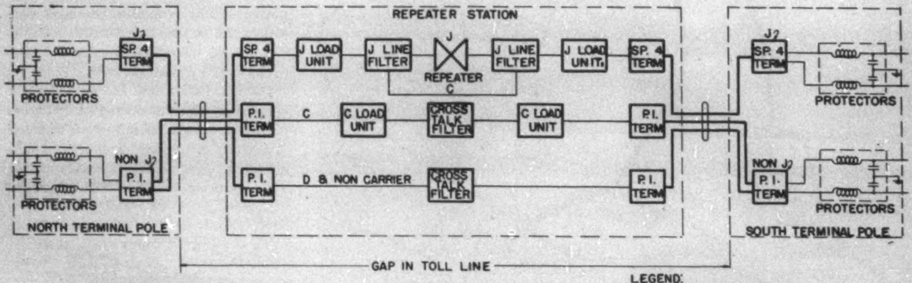
REPEATER STATION
J1
SP. 4 TERM
PROTECTORS
NON J2
P.I. TERM
PROTECTORS
NORTH TERMINAL POLE
SP. 4 TERM
J LOAD UNIT
J LINE FILTER
J
REPEATER
C
J LINE FILTER
J LOAD UNIT
SP. 4 TERM
P.I. TERM
C
C LOAD UNIT
CROSS TALK FILTER
C LOAD UNIT
P.I. TERM
P.I. TERM
D & NON CARRIER
CROSS TALK FILTER
P.I. TERM
J2
SP. 4 TERM
PROTECTORS
NON J2
P.I. TERM
PROTECTORS
SOUTH TERMINAL POLE
GAP IN TOLL LINE
LEGEND:
TERM. = CABLE TERMINAL
SP. 4 = SPIRAL FOUR
P.I. = PAPER INSULATED
= CABLE
= LONGITUDINAL RETARD COIL

Figure 6. Circuit connections through Temple unattended repeater station

each direction of transmission, the provision of two intermediate repeaters would provide sufficient gain to take care of the wet weather conditions with no extra margin; three repeaters would provide 45 decibels margin and four would provide 90 decibels margin for the over-all system. Considering the location of this line and the small probability of obtaining large deposits of ice in accordance with past experience, it was decided to select tentatively three intermediate repeater stations which would provide sufficient gain to take care of attenuation up to about 0.5 decibel per mile as compared to the wet-weather value of 0.35 decibel per mile.

For type *C* operation over this line, only one type *C* carrier repeater point is required, and it is at Austin. Considering the availability of power equipment and operating personnel and the possibility of future *J* carrier terminals being located at Austin, it is desirable that this be one of the repeater points on the *J* system. A division of the attenuation of the facilities north of Austin indicated that the other stations should be in the vicinity of Temple and Milford.

At these repeater stations amplification is needed only on the type *J* system and the other circuits on the line pass through these stations without amplification. Under these conditions energy may be transferred from the output of one type *J* repeater to the input of the same repeater or to the input of a repeater on another *J* system via cross-talk paths involving the wires which are not used for type *J* systems. The effect of this transfer of energy is accentuated by the fact that there is a large difference in transmission level between the output of one type *J* repeater and the input of the same or another repeater. In order to minimize these effects it is necessary that all wires on the line be given special treatment, including a gap in the toll line, longitudinal choke coils in all wires at terminal poles, and cross-talk suppression filters in the non-*J* pairs in the repeater station itself. In selecting locations for repeater stations, consideration must also be given to the possible coupling between type *J* systems by interaction paths involving other conductors adjacent to the toll line.

Before definite selection of repeater station locations may be made, it is necessary that each repeater section be checked in detail and in this check the entrance cable arrangement may be controlling. The newly developed spacer-insulated spiral-four cable, either loaded or nonloaded, or nonloaded pairs of the conventional paper-insulated cable may be used between the open wire and equipment. Generally the existing voice and *C* carrier circuits use loaded entrance-cable pairs and in most cases a change to nonloaded facilities would require extensive rearrangements in these circuits. In order to use nonloaded pairs for the *J* carrier and leave the *C* carrier and voice on loaded facilities, filters are placed at the terminal pole to separate the *J* carrier frequencies from the *C* and voice frequencies at that point. A limitation on the use of existing cable is that suitable pairs must be selected by cross-talk measurements and balanced at 140 kilocycles to meet the requirements of the system. The paper-insulated conductors have the largest attenuation of any of these facilities, and the loaded spiral-four the least. The various entrance arrangements from the open wire to the office equipment are described in more detail elsewhere.[3] The choice of the facility used in any particular case will depend upon the resultant over-all economy.

The large number of nonloaded pairs in the existing 1.8-mile entrance cable at San Antonio indicated that sufficient pairs could be selected which would be satisfactory from the cross-talk standpoint for *J* carrier operation. Six pairs were subsequently selected and balanced.

At Austin a single toll entrance cable, one mile in length, with two complements, terminates the line from the two directions. Although the two complements are separated by a layer shield, this cable is not suitable from a cross-talk standpoint for operation of the *J* carrier in and out of the office; therefore, at least one additional cable is required from the central office to the toll line. For this purpose a new nonloaded spiral-four entrance cable was indicated for the type *J* system with the type *C* and voice circuits continuing to use the existing cable. The separation of the type *J* circuits from the non-*J* circuits on the same pairs is accomplished by filters which are located in a small building at the junction of the toll line and the entrance cables. The use of a single entrance cable for the non-*J* wire in both directions on the telephone line indicated that it might be necessary in the future to use cross-talk suppression filters at this point. Accordingly, the filter hut was made large enough to include future cross-talk suppression filters if required as well as the line filters which separate the type *J* from the non-*J* circuits.

A repeater station at Temple could have been located in the existing central office or could be located in a separate building in or near the city. In either case a new power plant was needed since the existing plant could not be economically modified to serve the *J* carrier repeaters. The telephone line is continuous through the city, only those wires used for Temple circuits being terminated in the office through one entrance cable 0.6 mile in length. This cable is not suitable for *J* operation in both directions, which would require one additional cable if the repeaters were located in the central office. Numerous signal and supply lines in proximity with the telephone line within the city offered interaction crosstalk complications. A separate repeater station near the toll line in or near the city avoids the placing of a long entrance cable, reduces the over-all system attenuation, and eliminates the problem of interaction crosstalk from paralleling lines. Other factors including cost showed very little difference between a separate station and placing the repeaters in the central office. An unattended station near the toll line was indicated.

A common entrance cable at Dallas terminates the wire on both the Houston and San Antonio lines, the terminal of the Houston line being 2.9 miles from the central office, and of the San Antonio line one mile further. This cable previously had been placed in three different sections, each section having a different make-up, and there was considerable doubt as to the number of suitable pairs for *J* operation that could be obtained. The use of either a loaded or nonloaded spiral-four cable would not improve attenuation sufficiently to change the number or materially alter the locations of the repeater stations from those tentatively selected, but would provide some additional margin for sleet conditions. The expense of loading the spiral-four cable, if placed, could not be justified by the improvement in over-all attenuation. Using either nonloaded spiral-four or existing nonloaded paper-insulated conductors requires filters at the open-wire terminus. With these considerations, it was decided that suitable pairs would be used in the existing cable until exhausted. Subsequent cross-talk selection tests have indicated that 12 pairs, 6 for each line, are available.

Since there was no suitable central-office building at Milford, the repeater station in that vicinity must of necessity be in a new building preferably near the toll line. Commercial power is available only near the town, forcing a tentative location to be selected at the edge of the city.

With these selections of entrance-cable facilities and tentative repeater-station locations, the distribution of gain and line loss by repeater sections is shown in table I. A satisfactory distribution of line loss has been obtained and an analysis of these data shows that further improvement is impracticable. Therefore, the tentative repeater-station locations were adopted.

Figure 4 is a diagram of the major line and equipment parts of the Dallas-San Antonio lead. The *J* carrier path is shown by heavy solid lines, the *C* and voice on the same wire with the *J* by light solid lines, and all other circuits, classed as non-*J*, by dotted lines. Figures 5 to 7, inclusive, show in more detail the arrangements at the huts and repeater stations. The figures for the Dallas hut

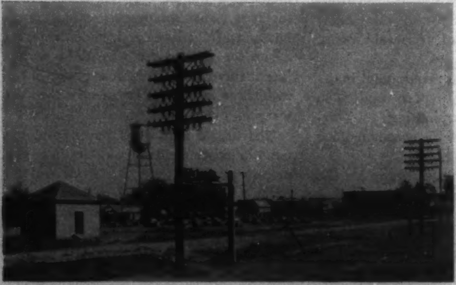

Figure 7. Arrangement of gap in toll line at unattended repeater station

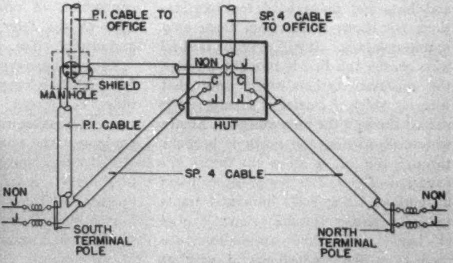

Figure 8. Cable arrangement at Austin

SP.4—Spiral four
P.I.—Paper insulated

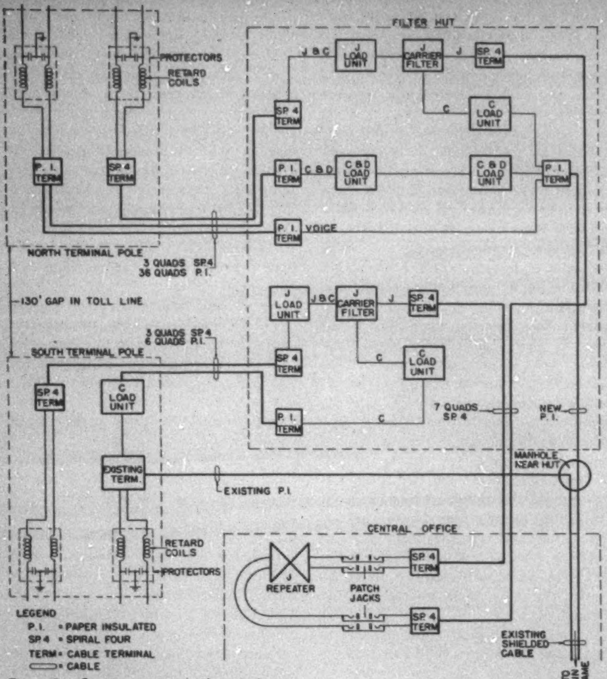
FILTER HUT
PROTECTORS
RETARD COILS
J B C
J LOAD UNIT
J CARRIER FILTER
J
SP. 4 TERM
C
C LOAD UNIT
SP. 4 TERM
P. I. TERM
SP. 4 TERM
P. I. TERM
C & D
C & D LOAD UNIT
C & D LOAD UNIT
P. I. TERM
P. I. TERM
VOICE
NORTH TERMINAL POLE
3 QUADS SP.4
36 QUADS P.I.
130' GAP IN TOLL LINE
J LOAD UNIT
J B C
J CARRIER FILTER
J
SP. 4 TERM
3 QUADS SP.4
6 QUADS P.I.
SOUTH TERMINAL POLE
SP. 4 TERM
C
C LOAD UNIT
SP.4 TERM
C LOAD UNIT
P. I. TERM
C
7 QUADS SP. 4
NEW P. I.
EXISTING TERM.
MANHOLE NEAR HUT
EXISTING P.I.
RETARD COILS
PROTECTORS
CENTRAL OFFICE
J REPEATER
PATCH JACKS
SP. 4 TERM
SP. 4 TERM
EXISTING SHIELDED CABLE
TO MAIN FRAME
LEGEND
P. I. = PAPER INSULATED
SP.4 = SPIRAL FOUR
TERM = CABLE TERMINAL
= CABLE

Figure 9. Circuit connections through Austin

and Temple repeater station are typical, and huts and unattended repeater stations not shown differ from these only in minor details. It will be noted that all wire on the toll line is brought through the repeater stations while only that wire on which *J* carrier is superposed is routed through the huts except at Austin where all wire to the north is brought through the hut to allow the future application of cross-talk suppression filters if required. For both huts and unattended repeater stations, short lengths of loaded spiral-four conductors are used from the six-inch-spaced wire at the terminal poles to the equipment in the buildings. A single continuously adjustable load unit is used for each pair and is located with the equipment. Paper-insulated pairs under the same cable sheath as the spiral-four conductors are used for the non-*J* wire.

As previously mentioned, the conditions at Austin were complicated by a single cable for existing circuits and a new cable for *J* carrier in both directions. Figure 8 is a diagram of the existing and new cables to the filter hut and terminal poles, and figure 9 shows the interconnection of circuits and equipment used at the filter hut, terminal poles, and central office.

Terminal and repeater equipment in existing offices is located in space adjacent to other equipment terminating toll circuits, and makes use of the common office equipment and power plant.

The new repeater stations and the filter huts are arranged for unattended operation. The equipment in the filter huts is such that no adjustments or attention are required other than periodic inspections. In the unattended repeater stations the power-supply equipment is automatic in its operation. Although periodic maintenance attention is necessary, it is desirable that any abnormal condition be recognized as soon as practicable and a system of alarms has been provided from each unattended station to an adjacent main repeater or terminal office. This alarm has been arranged to operate by direct current over one conductor between offices without interfering with existing telephone circuits but at the expense of one d-c telegraph path. For fuse failure, rectifier failure, power off, power restored, high-low voltage, high-low temperature, fire, burglary, pilot channel failure, and end of pilot channel control, alarms are sent and identified. A questionable alarm may be rechecked from the attended office.

Special Problems

Some of the problems encountered in connection with the other two systems may be of interest. At Corsicana, a repeater point on the Dallas-Houston system, a filter hut was used on only one side of the repeater station. The situation which led to this arrangement is that an intermediate cable in the Dallas-Houston line extends 0.2 mile north and 0.5 mile south from the local central office. As it is necessary that the *J* system operate through this entrance cable and since space was available in the local central-office building, repeater equipment similar to that installed in unattended buildings was placed in one room in the office.

The section of cable north of the central office terminates on a corner in a business district with all adjacent property occupied by buildings, making it more economical to use loaded spiral-four cable to this location rather than extend the existing cable to an available site and provide the necessary filter hut and equipment. For the longer cable, it was more economical to provide the filter equipment in a hut in order to use existing facilities. Although this cable terminates in a fully developed residential area, a site for a filter hut was obtained adjacent to an alley in the rear of one of the residences facing the street on which the terminal pole is located.

The use of nonloaded paper-insulated pairs in existing entrance cables has been mentioned. However, it is in general not practicable for cross-talk reasons to use all the nonloaded pairs which are available in one cable, and the selection of pairs suitable for type *J* operation is illustrated by a discussion of the methods used on the Dallas cable. The Dallas cable is composed of three sections of different make-up. The section nearest the central office, 1.3 miles long, and the intermediate section, 1.6 miles long, each contained 22 idle nonloaded pairs, and the third section, one mile long, had only 6. The Houston line terminates at the end of the second section, the third section extending the cable to the San Antonio line.

Since the number of cable pairs to the San Antonio line was limited to a maxi-

Table I. Distribution of Gain and Loss by Repeater Sections

Repeater Section	Cable Length (Miles)	Cable Loss (Decibels)	Open Wire Length (Miles)	Open Wire Wet Weather Loss (Decibels)	Maximum Tolerable Attenuation in Decibels per Mile at 140 Kilocycles Using 45-Decibel Repeaters	Maximum Tolerable Attenuation in Decibels per Mile at 140 Kilocycles Using 75-Decibel Repeaters
Dallas-San Antonio system						
Dallas-Milford	3.9 miles 16 gauge	17.50	49.2	16.4	0.560	1.165
Milford-Temple	Nominal	Nominal	84.7	27.3	0.532	0.885
Temple-Austin	1.1 miles spiral-4	2.20	74.4	24.8	0.575	0.980
Austin-San Antonio	1.1 miles spiral-4 1.8 miles 16 gauge	10.30	78.5	26.2	0.635	0.825
Dallas-Houston system						
Dallas-Corsicana	2.9 miles 16 gauge	13.20	52.5	17.5	0.610	1.175
Corsicana-Hearne	0.5 miles 16 gauge	2.25	90.5	30.2	0.484	0.805
Hearne-Hockley	Nominal	Nominal	85.6	28.6	0.545	0.875
Hockley-Houston	5.6 miles 16 gauge	25.20	29.1	9.7	1.190	1.700
Dallas-Longview system						
Dallas-Edgewood	1.4 miles 16 gauge	6.30	55.3	21.0	0.984	1.240
Edgewood-Longview	0.5 miles 16 gauge	2.30	69.7	26.5	0.614	1.040

mum of six and since the rate of circuit growth over the two lines was expected to be approximately the same, requiring cable relief over the entire distance when the branch to the San Antonio line was exhausted, an objective of six pairs to each line was set up.

Measurements of cross-talk coupling at 140 kilocycles in terms of inductance and capacitance unbalance were made between each pair and all other pairs in each section and the pairs rated in their order of desirability. It is of interest that this required a total of 854 measurements. Those pair combinations whose coupling of the mutual-inductance type was high were rated as the least desirable. This was done because capacitance balancing was to be used to obtain cross-talk reduction. The more desirable pairs in the first two sections were connected through to the six pairs in the last section by cut-and-try method until the over-all condition was such that all six pairs were acceptable. By a similar procedure, using the remaining pairs in the first two sections, six pairs to the Houston line were made acceptable. No record is available as to the number of tests made in the cut-and-try process.

A cable terminal on which balancing capacitors were mounted was installed in the central-office building and connected to the selected pairs. This terminal contained 66 small adjustable wire-wound capacitors which were connected between each pair and every other pair. The capacitors were adjusted to reduce to a minimum the capacitance component of the cross-talk coupling.

Buildings

For the three *J* carrier systems, four new repeater stations and eight filter huts were needed. The same type of construction was used for all: concrete foundation with floor slab above grade, double four-inch brick walls with rock-wool insulation between but with solid brick at corners and openings, pitched roof with wood framing, fire-resistant wallboard ceiling, fire-resistant composition shingles, and heat insulation above ceiling and below floor slab.

All of the racks for equipment in the unattended repeater stations are arranged in three rows with power, repeater, and line equipment in separate rows within a floor space of 17 feet by 16 feet which will allow the ultimate installation of six repeaters in each building. The entrance cables from the terminal poles enter from iron conduit through the floor and are racked and spliced on the side wall adjacent to the line bays. The stubs from the cable terminals at the top of the line bays are carried overhead to splices on the wall. A ceiling height of 13 feet is maintained above the equipment but reduced along the pitch of the

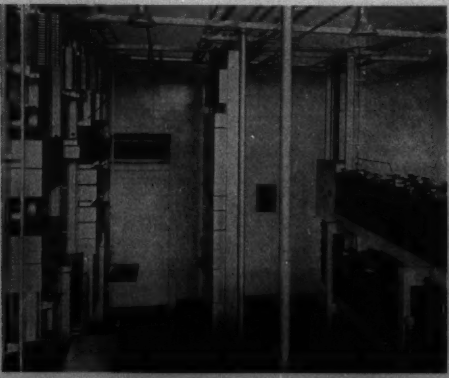

Figure 10. Equipment in unattended repeater station

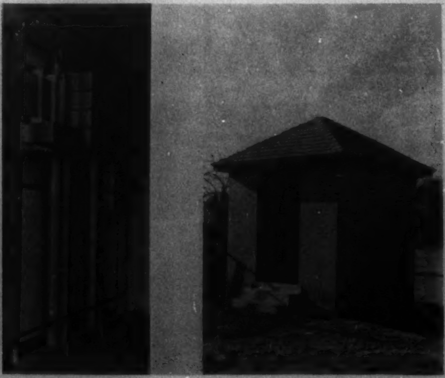

Figure 11. Typical hut and filter equipment

roof to 11 feet 8 inches at the side walls.

For all huts except that at Austin, three adjacent bays of racks are needed. With these along one side wall of the hut, the opposite side is available for splicing the entrance cable. At Austin an ultimate of nine racks, for filters in both directions of transmission, led to the use of racks along opposite sides of the hut with a splicing pit under the floor made accessible by trap doors in the floor between the lines of racks. In this case, the cable terminals are installed at the bottom of the racks with their stubs dropped directly through the floor slab into the splicing pit. The racks in the hut are seven feet high and a ceiling height of eight feet is used. Figures 7, 10, 11, and 12 are pictures of a typical repeater station, typical filter hut, and the special hut at Austin.

For correct operation of the equipment, temperature limits of 32 to 110 degrees Fahrenheit are desirable. Also, it is necessary that there be no precipitation of moisture on wiring or equipment. To maintain the desired conditions, each of the huts is equipped with a two-kilowatt blower-type electric heater arranged to operate at low temperature or high relative humidity, but with operation blocked when the temperature reaches 95 degrees. Each new unattended repeater station is equipped with a four-kilowatt heater similarly controlled and, on account of the heat dissipation of power plant and vacuum tubes, also has forced ventilation which is operative under conditions of high temperature. The system of forced ventilation consists of spun-glass intake filter, exhaust fan, electric-solenoid-controlled shutters at intake and exhaust, and thermostat, and is interconnected with the office alarms to prevent fan operation in case of fire.

Conclusion

Upon completion of the buildings, equipment installation, and line-facility rearrangements, adjustments in the equipment were made to match the lines used. Networks associated with the terminal and intermediate amplifiers were adjusted so that the amplification for any particular frequency would be equal to the attenuation at that frequency in the preceding repeater section; the automatic pilot channel equipment[1] compensates for attenuation changes. In repeater sections containing long toll entrance cables, it was necessary to sacrifice range of automatic pilot channel control to obtain the best equalization. However, satisfactory equalization and range of pilot channel control were obtained in every case.

As mentioned previously, the Dallas-Longview system operates on 12-inch spaced phantomed wire. In figure 13 the attenuation characteristics of two possible pairs are shown. The absorption peaks of pair *B* at 92 and 127 kilocycles are within the frequency range of channels number 4 and 12 of the *J* system and would impair the quality of those channels if pair *B* were used. Therefore, pair *A* is used as the regular path for the system. The quality of the channels obtained from these systems is shown by figure 14. Curve *A* is representative of that obtained from a system operating over six-inch-spaced wires; *B* and *C* are the best and poorest obtained from the Dallas-Longview system.

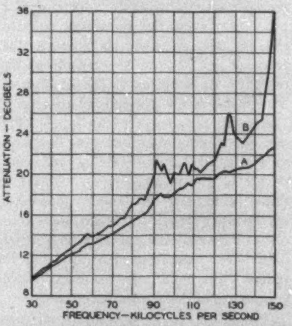

Figure 13. Attenuation of two 12-inch-spaced phantomed pairs of the Edgewood-Longview repeater section

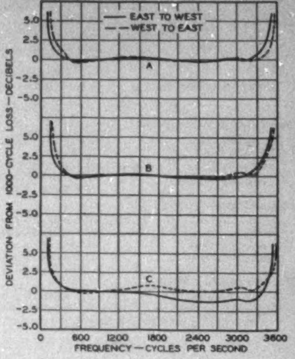

Figure 14. Quality of derived circuits

A for typical channel of systems on six-inch-spaced wire, *B* and *C* for the best and poorest channels of system on 12-inch-spaced wire

The Dallas-San Antonio, Dallas-Longview, and Dallas-Houston systems were placed in commercial service in September, October, and November 1938, respectively. Experience with these systems is that the circuits obtained compare favorably with those obtained from any other facilities in quality and continuity of service, and that a definite need has been fulfilled in providing an economical method of increasing the capacity of the existing plant.

References

1. A 12-Channel Carrier Telephone System for Open-Wire Lines, B. W. Kendall and H. A. Affel. AIEE Transactions, volume 58, 1939, pages 351–60 (July section).

2. Line Problems in the Development of the Type J Open-Wire Carrier System, L. M. Ilgenfritz, R. N. Hunter, and A. L. Whitman. AIEE Transactions, volume 58, 1939, pages 656–65 (December section).

Discussion

Earl W. Lipscomb (Western Union Telegraph Company, Dallas, Tex.): In view of the practice of loading cables for use in voice and carrier circuits up to about 30 kilocycles, it is somewhat striking to note that loading is not used for the *J* frequencies, although greater normal attenuation and greater loss from impedance mismatch

Figure 12. Austin hut and filter equipment

would be expected at these higher frequencies. The necessity for closely spaced loading coils at *J* frequencies may make loading prohibitive, but it would be interesting to know of the measures used to minimize high-frequency losses in standard nonloaded paper-insulated cable.

Treatment is prescribed for wires on the line which are not used in *J* systems to prevent their coupling the high output of the *J* repeaters back into the input of these repeaters. Similar difficulty may be experienced from wires on adjacent pole lines owned by other companies. While it may be possible to apply the same treatment to the foreign-owned wires and lines, it would be of interest to know something of the losses these measures would introduce into the foreign circuits. It appears that the problem may become more difficult in the event that the other companies desired to use similar high frequencies on their circuits. Field tests during the installation of the *J* systems probably have indicated a separation between lines beyond which the coupling effect need not be considered.

T. L. Keathley (Southwestern Bell Telephone Company, Houston, Tex.): In the paper so ably presented by Messrs. Starbird and Mathis on the subject: "Some Applications of the Type *J* Carrier System" you were told that four circuits of 0.128 copper wire were placed on pole-top extension fixtures on the Dallas-Houston and Dallas-San Antonio lines. It was also pointed out that the two wires forming a circuit were only six inches apart and transposed on point side transposition brackets at an average interval of 260 feet or on every other pole in the line. Several unusual and interesting construction features were involved in the operation of placing this wire.

The crossarm positions on a pole line are termed gains, and are numbered from the top downward. Incidentally, this will explain the derivation of the term "zero gain" which has been applied to the arm on the pole top fixture. Since the existing top arm is designated as the first gain, anything above that must have a lower number, and zero has been selected. Ordinarily the crossarms and wire are added to a pole line from the top downward; but this order is reversed in the case of placing wire in the zero gain. The new wire must be placed above the working circuits and it is very important that it be kept clear of the existing wire during the placing to avoid service interruptions. This is done by placing what is known as an extension side arm fixture on each of the arms on which the new wire is to be placed. This side arm is a two-inch by four-inch piece of timber three feet in length with four notches at one end to engage the new wire. At the other end and also at an intermediate point, this side arm is equipped with S-shaped strap-iron brackets, which hook under and over the arm that is to carry the new wire, the notched end extending beyond the crossarm.

After the wire is pulled out on the ground in 0.7-mile lengths, it is placed on the extension crossarm by laying-up sticks made of long cane poles with hooks on one end. Should the poles be high, linemen climb the poles and raise the wires to the sidearms with hand lines. The final sag and adjustment is then made by pulling at short intervals, this being necessary because the numerous transpositions in the circuits are effected on six-inch point side brackets and the line wire will not adjust itself around these brackets without some assistance. Each of these brackets has four pins for making the transpositions and is so arranged that one pin of each pair is higher than its mate; this is done in order that the left-hand wire (going in direction with the line) can pass over and change positions with the wire on the right, and at the same time afford clearance between the two conductors.

The spans on these leads averaged about 130 feet, and sag requirements on this length of span at 70 degrees Fahrenheit is 9$^1/_2$ inches. Seventy degrees Fahrenheit is being quoted as that was about the average temperature prevailing at the time wire was placed.

Ordinarily, where wire is being sagged and the regular one point drop brackets are used, lengths of approximately one mile can be pulled on straight runs, but, due to the slack required at the numerous 6-inch point side brackets, shorter pulls had to be made, and a rather novel arrangement was worked out.

A groundman stationed at the sagging blocks was equipped with a 62-*A* test set. The tying crew consisted of four linemen, two of whom where also equipped with small test sets attached to one of the new circuits. The men with test sets worked on transposition points at all times, and the others on intermediate poles. When the proper sag was obtained through telephone conversation with groundman at the blocks, all four men completed their ties and each proceeded four poles forward and repeated the operation.

It might be of interest to know that in placing the four circuits of wire between Dallas and San Antonio and between Dallas and Houston, a distance of 555 pole miles, the following material was involved:

1,173,760 pounds of 128 copper wire amounting to 2,240 circuit miles

33,600 six-inch side point transposition brackets

20,640 H-beam pole-extension fixtures

22,880 eight-pin six-inch-spaced crossarms

266,400 Pyrex insulators

A total of 82,400 manhours, or 10,300 mandays of labor were required in placing the wire, extension fixtures, crossarms, and other associated materials. An oddity, in connection with material used on this project, is that approximately two miles more wire was required due to the use of point-side transpositions than would normally be required on ordinary brackets.

R. P. Brown (Southwestern Bell Telephone Company, Dallas, Tex.): The paper, "Some Applications of the Type *J* Carrier System," presented by Messrs. Starbird and Mathis brings out that the first three commercial installations of these systems were made in Texas. This is of considerable significance and brings about a thought as to what condition existed in Texas that would necessitate three separate installations of these systems so soon after the development and all about the same time. It is about this condition that my discussion will be confined.

In the national plan for handling intercity toll communications, there have been designated eight regional centers so located as to serve certain areas and each connected to all the others with direct lines so as to minimize the number of switches and furnish the highest possible grade of toll service. In the Southwestern area one of the regional centers is located at Dallas, and for handling the toll traffic in the area and connecting Dallas with the other regional centers there are seven major trunk routes through Texas which are described as follows:

(*a*). Dallas-Houston
(*b*). Dallas-San Antonio
(*c*). Dallas-Longview
(*d*). Houston-Beaumont
(*e*). Cisco-West
(*f*). Dallas-Red River (Oklahoma)
(*g*). Dallas-Cisco

The latter two mentioned which required relief before the conception of the 12-channel open-wire carrier were cared for by the placing of underground toll cable during 1930.

At that time the question of relief on the other trunk routes was becoming pressing and relief by placing cable seemed to be the proper method. Studies were prepared on that basis and as the relief was first necessary in the sections to Houston and San Antonio an inverted Y layout with the base at Dallas, the fork near Waco, and the two branches extending to Houston and San Antonio appeared to be the plan to follow. The Longview and Beaumont cables would follow later as would the extension of the Dallas-Cisco cable beyond Cisco.

To care for the growth until the cable relief was forced the open-wire pole lines were being developed to the maximum circuit possibilities by the use of the single- and the three-channel open-wire telephone carrier systems. Under this expansion the physical wire had grown to about five crossarms and by using the various instrumentalities the telephone circuit possibilities had been expanded to approximately 70 circuits.

With the information that a new carrier system was being developed that could be superposed on some of the present wire without sacrificing any of the present telephone circuits, thereby providing 100 or more additional telephone circuits, and which could be grown in groups of 12 telephone channels at a time without an extreme expenditure for the initial installation, it was apparent that this new development was just the thing required here in Texas to care for our problem and the first question was just how quickly could it be made available. As a result, the plans for relief by the placing of toll cables were laid aside and new plans developed on the basis of using the equipment that was under development and which would be rushed to completion due to the immediate requirement.

To use the newly developed 12-channel system on present open-wire leads it would be necessary to do some wire respacing and retransposing before the second system is installed; however, with the initial installation sufficient circuits would be available to care for growth and still allow present wire to be taken out of service for the rearrangements required to make the future additions. Where the circuit requirements could be cared for until the new carrier became available, as in the case of the Dallas-Longview line, the first installation would be placed on present wire and then the rearrangement work carried out, but in the cases where additional circuits had to be made available immediately, wire properly spaced and transposed for the new carrier system was placed and growth cared for using present available equipment until the new equipment was ready.

With the placing of the 12-channel systems in service for the longer distances it becomes possible to relocate the present terminals of the one- and three-channel systems to intermediate points in these trunk routes as well as in other sections, creating a very flexible circuit arrangement.

In conclusion it appears that the development of the new 12-channel open-wire carrier system was completed just in time to fit into the toll-line plan for Texas and definitely postpone for a considerable time the placing of toll cables over new routes.

R. B. Webb (Southwestern Bell Telephone Company, Dallas, Tex.): The development of a new toll instrumentality such as the type *J* carrier system immediately raises the question as to where this type of carrier can be most advantageously applied. Each major open-wire toll line must be studied to determine if the expected growth can be cared for most economically by providing additional physical circuits, additional three-channel and single-channel carrier systems, the use of the type *J* carrier systems, or by different combinations of all of these methods of relief.

The first step involved in the preparation of a toll line study is to secure a large amount of basic data, the chief elements of which are as follows:

1. Estimate of circuit requirements on the toll line, by circuit groups for several years into the future.
2. The present circuit arrangement and the number and types of carrier systems already in use on the line.
3. Basic toll-line data, covering the age of the line, pole heights, number of crossarms, and the maximum number of crossarms that can be placed.
4. Toll-entrance-cable data, listing the length, gauge, and number of conductors in the toll entrance cable at each central office involved.
5. The number and location of present carrier repeater stations.
6. The number and approximate location of repeater stations required for *J* carrier.

The most feasible plans of caring for the growth are developed from an analysis of the requirements and the local situation. The period of the study is determined by local conditions, although in general it is desirable to carry the study to a date after which the facilities will be common under all plans. Circuit layouts are made for each year considered, and all circuit additions and rearrangements, and the means used to effect them, are indicated by appropriate codes. These circuit layouts give, by successive steps, the complete program of caring for the growth under each plan during the study period.

The long-distance network is so complex that it is frequently necessary to include on the circuit layouts much more of the toll plant than the particular toll line under consideration. For instance, in the Dallas-Longview study, it was necessary to include the Longview-Shreveport line, the Longview-Jacksonville-Tyler line, and the Tyler-Mineola line. In so far as possible, the same number of toll circuits is cared for under each plan, and, if this is not done, the difference in facilities provided must be considered in interpreting the financial results of the study.

After the circuit layouts are developed, the additional outside plant construction, central-office equipment, and other items can be priced, and the total capital requirements obtained. Engineering cost studies are then made to determine the annual charges and operating expenses for each plan. The financial results thus obtained will usually indicate the proper method of toll-line relief.

The general study methods just outlined were employed in 1936 to determine the proper relief program on the Dallas-San Antonio, Dallas-Houston, and Dallas-Longview toll lines. Because each of these toll lines was approaching its maximum fill and because of the circuit growth expected, it was evident that the initial *J* carrier installation should be made on each of these lines either in 1938 or 1939. As the three toll-line problems were very similar it will only be necessary to comment on the Dallas-San Antonio study.

In this study, it was only necessary to determine what the penalties would be for deferring the *J* carrier from 1938 until 1939. It developed that thus deferring the *J* carrier relief would have required the stringing of so much toll wire and the placing of so many three-channel carrier systems that it was obviously an uneconomical procedure, and the installation was therefore carried out in 1938.

In this particular case, the study solution to the problem appeared fairly obvious from the start, since the circuit growth was about 12 circuits a year. However, in the case of a toll line not so heavily loaded, and where the annual growth is not so rapid, the economical time to install the initial *J* carrier will not be so apparent. For instance, in the study on the Houston-Beaumont toll line, the circuit growth was only about six circuits a year. The two plans of relief considered were: first, to install an initial *J* carrier system in 1939 and additional *J* systems as required; second, to provide other facilities in 1939 and 1940 and install the initial *J* carrier in 1941. This study was carried out over a ten-year period in order to make the two plans as nearly comparable as possible. It was found that the *J* carrier system should be installed in 1939 and this system will be placed in service in May of this year. Studies are to be made on other open-wire toll lines to determine when and where the type *J* carrier should be used.

L. C. Starbird and J. D. Mathis: The comments by Messrs. Keathley, Webb, and Brown are of interest in that they present additional information about the problems encountered in the application of these systems, together with amplification of some of the items mentioned in the paper. Mr. Lipscomb's comments leave several unanswered questions.

In regard to the use of nonloaded paper-insulated pairs for the *J* frequencies versus loaded pairs for the *C* frequencies, the normal attenuation of the nonloaded paper-insulated pairs is unfortunately very high. However, because of the close spacing of load coils required to load these conductors at *J* frequencies it is generally more economical to provide sufficient amplification to override the loss than it is to provide the loading. Impedance-matching transformers are provided at the filter hut and in the central office to minimize the loss to the *J* system and the crosstalk between systems that would be caused by an impedance irregularity. Nonloaded cable pairs may also be used for the *C* frequencies; however, in the application discussed, loaded pairs were already available for the *C* systems, and it was more economical to use these than to provide the amplification and impedance matching required if nonloaded pairs were used.

In regard to possible measures of reducing cross talk caused by paralleling wire near a *J* carrier repeater station, except for the more severe cases, this cross talk will be chiefly caused by longitudinal current which may be sufficiently suppressed by the insertion of longitudinal choke coils only. These coils have practically no effect on metallic currents and would not interfere with the operation of a carrier system over the paralleling wire at frequencies up to about 150 kilocycles. In the more severe cases of parallel it would be necessary to insert cross-talk suppression filters in the paralleling wire. The loss caused by these filters in the pass band is from about 0.1 decibel at voice frequency to 0.7 decibel at 30 kilocycles for each point where applied. In case the paralleling wire is to be used for carrier current at frequencies above 30 kilocycles, it will be necessary to co-ordinate repeater-station locations in order to prevent level differences. By co-ordinating repeater locations, the filters required on each line because of the systems on that line would serve to minimize the interaction cross talk without other special measures.

The questions are discussed in more detail in the papers listed as references and in the discussion with reference to those papers.

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DAYS KERITE

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Industrial Notes

New Western Electric Subsidiary.—To meet the requirements of broadcasting stations, airlines, the government services and other similar users of its communication equipment outside of the Bell System, the Western Electric Company has formed a new branch to be known as the Specialty Products Division. This unit will be responsible for such by-products of telephone research as hearing aids; aviation, marine and police radio; broadcasting equipment; sound systems and equipment made to specification for the United States government. The new division, which began formal operation last month, is located at the Kearny, N. J., works of Western Electric, with F. R. Lack as manager. Mr. Lack has been associated with the Bell System since 1911.

New Division for Copperweld Steel.—Frederick J. Griffiths has been appointed executive vice-president in charge of the newly created alloy steel division of the Copperweld Steel Company. The appointment follows the earlier announcement by S. E. Bramer, president, that the Copperweld Steel Company had purchased the plant and assets formerly owned by the American Puddled Iron Co., Warren, Ohio. On the 423-acre property a $2,000,000 steel plant will be erected, including electric furnaces and other equipment capable of producing 100,000 tons of high quality alloy steel annually, part of which is to be used in the manufacture of Copperweld wire, rods, and strands of copper-covered steel. The present buildings of the American Puddled Iron Company will furnish only a nucleus for the new plant which, when completed, will spread over 285,000 square feet of floor space. The finishing operations now being carried on in the Copperweld Steel Company's plant at Glassport, Pa., will continue as usual.

Expands Engineering Department.—A new engineering building is under construction for Walter Kidde & Co., makers of carbon dioxide fire extinguishing equipment, widely used in the electrical field, on the company's manufacturing site at Bloomfield, N. J. The new structure, to be devoted exclusively to engineering and research work, will house a large staff of engineers when completed. Commenting on the announcement of the new addition, President Walter Kidde cited the branching of the company into new fields, which calls for enlarged engineering facilities.

Roller-Smith Appointments.—New sales agencies recently appointed by the Roller-Smith Company, Bethlehem, Pa., include J. J. Thalheimer, 242 Fountain Ave., Dayton, for southern Ohio, southern Indiana and Kentucky; Walter V. Gearhart Co., Volunteer Bldg., Atlanta, for the states of Georgia, North and South Carolina and parts of Alabama and Florida; and the Public Service Supply Co., Inc., Midland Bldg., Cleveland, to cover the utilities in northern and southeastern Ohio.

Roebling Moves New York Office.—The John A. Roebling's Sons Co., Trenton, N. J., manufacturers of wire and wire rope, insulated wire and cables, and wire cloth and netting, has moved its New York City offices from 107 Liberty St., to the 20th floor of 19 Rector Street.

Cutler-Hammer Appointments.—Terry Fisher has been appointed to take charge of the northern Indiana territory for Cutler-Hammer, Inc., with headquarters at South Bend. Clayton P. Innes is now representative in the company's Omaha territory.

Larger Quarters for Littelfuse.—For the fifth time in 12 years, Littelfuse, Inc. has been obliged to enlarge its manufacturing facilities, increase its plant capacity and move to enlarged quarters. The new plant address is 4757 Ravenswood Ave., Chicago.

Trade Literature

Relays.—Catalog, 32 pp. Describes relays, timing devices, and thermostats; prices are included. Struthers Dunn, Inc., 1315 Cherry St., Philadelphia, Pa.

Synchronous Motors.—Bulletin GEA 1191B, 52 pp. Describes in detail the characteristics, advantages and applications of synchronous motors; profusely illustrated. General Electric Co., Schenectady, N. Y.

Megohm Bridge.—Bulletin 459, 4 pp. Describes a new, type 544B, megohm bridge and its 500-volt power supply, for insulation resistance measurements. General Radio Co., Cambridge, Mass.

V-Belt Drives and Motors.—Bulletin B 6029, 28 pp. Includes comprehensive data in ready reference form for estimating costs, types and sizes of "Texrope" drive equipment and motors to be used under various operating conditions. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Lightning Arresters.—Bulletin GEA 1304F, 20 pp. Describes "Thyrite" station-type, lightning arresters applicable either indoors or outdoors for the protection of large or small generating or substation equipment. General Electric Co., Schenectady, N. Y.

Radium Detector.—Bulletin "E," 4 pp. Describes a Geiger counter type radium detector for discovering lost radium and for prospecting for radioactive materials, investigations in radioactivity, etc. Geophysical Instrument Co., 1315 Half St., Washington, D. C.

Switch and Bus Insulators.—Catalog, 18 pp. Describes a new line of bus and switch insulators assembled with an improved asphaltic compound known as "Permalastic" which, according to the manufacturer, tests have shown adds many years to insulator life. Complete data is given on all standard NEMA and several specially designed switch and bus insulators. Conductor clamps, adapters and spacers are also described. Porcelain Products, Inc., Parkersburg, W. Va.

Porcelain.—Bulletin, 12 pp. "A Survey of Technical Characteristics of Molded Ceramic Products" for wiring, heating and special purposes. Details the physical properties and applications of specific ceramic formulas. The Star Porcelain Co., 11 Muirhead Ave., Trenton, N. J.

Lathes.—Catalog 100, 112 pp. Said to be the most complete lathe catalog ever published; contains over 250 illustrations and shows 75 different sizes and types of back-geared, screw cutting lathes for production manufacturing, tool room and general shop work. South Bend Lathe Works, South Bend, Ind.

Underground Multiple Connectors.—Bulletin, 4 pp. Largely an illustrative treatment of the application of Burndy "Moles," (multiple tap connectors) available in many types, for underground secondary distribution systems. Features include elimination of soldering and junction boxes; cables with different types of insulation may be joined; installations can be made in limited space and in much less time than required for soldered, multiple splices; different cable sizes are accommodated in each outlet and provision made for rapid future connections. Burndy Engineering Co., Inc., 459 E. 133d St., New York City.

Varnished Cambric Cable Specifications

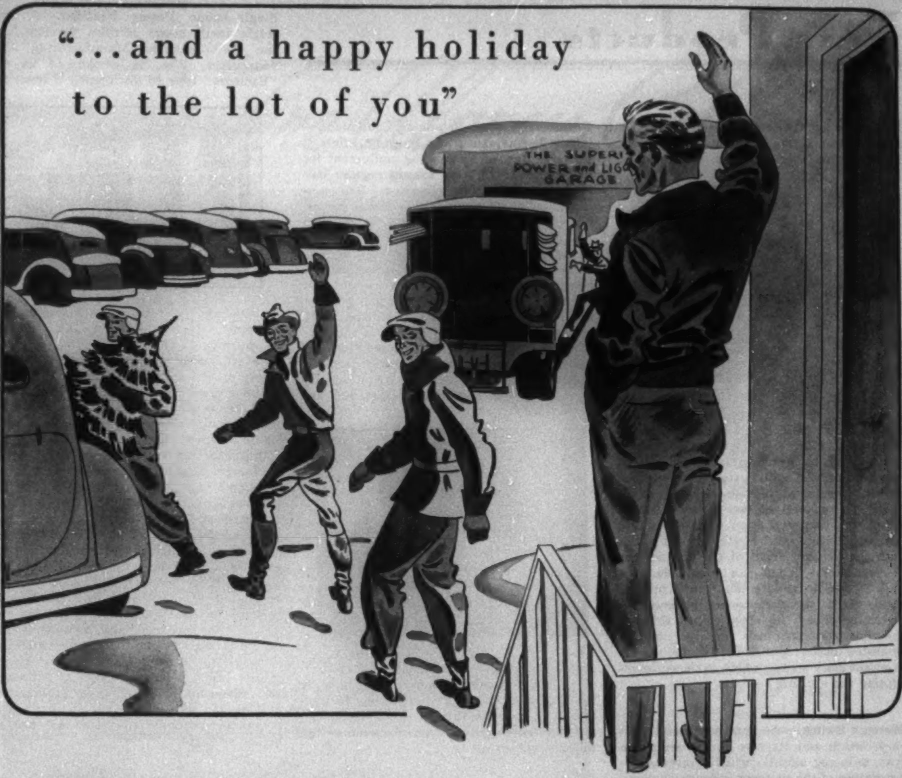
The Insulated Power Cable Engineers Association has recently issued a Fourth Edition of its "Specifications for Varnished Cambric Insulated Cables." This revised edition contains many changes which improve the accuracy and extend the scope of several sections and tables, bring certain requirements into conformity with the latest editions of correlated existing specifications, and insure the furnishing of cable embodying improvements in materials and manufacturing technique which have been made since the third edition was issued in 1934.

Probably the most important of these changes is the increase, ranging from 8° to 15°C. in the permissible maximum cable operating temperature over that previously permitted.

The Association calls attention to an important change in the title of Table VII, on page 8 of the Fourth Edition, which should read—"Recommended Thickness of Insulation—Single Conductor Cable and Multiple Conductor Shielded Cable."

Copies of the Specifications (28 pp.) are available without charge upon request to the Insulated Power Cable Engineers Association, 420 Lexington Ave., New York City.

"...and a happy holiday to the lot of you"



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A.C.S.R. conductors have high strength, long life and ample conductivity. Spans can be long and first costs low, without sacrificing quality. Let us assist you in engineering your next line; we'll supply you with data on any type of construction. Aluminum Company of America, 2149 Gulf Building, Pittsburgh, Pennsylvania.

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Aluminum Cable Steel Reinforced

FOR RURAL LINES AND POWER TRANSMISSION

New Products

Disconnecting Switch.—A recent development of the James R. Kearney Corp., St. Louis, Mo., this by-pass disconnecting switch may be used for isolating current transformers and voltage regulators without interrupting main line service. The main blade is composed of two separate blades which are insulated from each other and are respectively and electrically in series with the primary leads of the transformer or regulator. When the main blade is pulled open to isolate the transformer or regulator, a short circuiting blade automatically closes the main circuit through the line-side terminals of the switch. Mounted on the right side of the main blade is an auxiliary switch which is shown interrupting the exciting current.

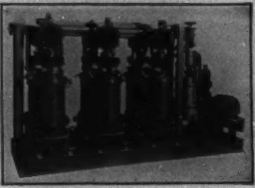
Mercury Switch.—An improved metal mercury switch and its new double reduction (two reducing agents) which prevents deterioration of the mercury, eliminates possibility of contact interruptions, increases efficiency and reliability in operation, according to the manufacturer, Durakool, Inc., Elkhart, Ind. It is reported to be the only commercial mercury switch available with over 40-ampere capacity, and up to 200 amperes (larger on special order), and is said even to withstand temporary short circuits, and to operate on small tilt with remarkably little energy. The improved switch allows many new applications from wall switches to motor starters and is now in use on electrical devices requiring from a few operations a month to 2,400 a minute.

Portable Dynamic Balancing Equipment.—The General Electric Company offers a portable dynamic balancing equipment for use wherever rotating masses require balancing to eliminate vibration. The new device is a self-contained precision instrument, capable of measuring the amount and phase angle of unbalance vibration present in the bearing pedestals of a rotating machine running in its own or substitute bearings, at any speed between about 600 to 5,000 rpm. Being portable, it permits the balancing of rotating equipment without the removal of the rotor from the machine and the balancing of rotors that are too heavy for previously available portable balancing machines. Because the balance is made under operating conditions, this equipment improves the quality of the result, as the changes effected by load and by the foundations are included. It has also been found a time-saver in balancing auxiliary equipment in control stations and manufacturing plants.

Illuminated Magnifier.—Developed originally for examining the inside portion of a valve and valve seat, the "Pike-O-Scope," an illuminated magnifier, also can be used for inspection of many other types of machinery.

A set of achromatic triple lenses are lighted by a special lamp built into the bottom of a cylinder which also serves as a handle. It may be attached to any electric outlet or used with dry cell batteries. The lamp cylinder and the threaded ring for the lenses are made of a heavy, shock-resistant, Bakelite molded material. It is said that defects can readily be seen at a distance of two feet from the eye.

Single-Anode Power Rectifier.—A new single anode power rectifier developed by the Allis-Chalmers Manufacturing Co., Milwaukee, Wis., is designated as the "Excitron" type to distinguish it from the multi-anode type also manufactured by the company. Instead of having all the anodes in one vacuum chamber, the Excitron consists of factory-assembled groups of relatively small vacuum tanks, each containing a single anode and its individual cathode. The tanks, which are externally cooled by water, are generally mounted in groups of six on a heavy structural steel frame. This frame also supports the vacuum pumping equipment, which is connected to the tanks through a vacuum pipe manifold. The arc ignition and control equipment, too, is mounted and wired on this frame. The single-anode Excitron unit is particularly suited for applications where the amount of available head room is limited. Due to the closer spacing between an anode and its associated cathode than in the multi-anode type of rectifier, the voltage drop in the mercury arc is reduced and, as a result, the company claims that the efficiency of the Excitron unit is from 3 to 4 per cent higher in the lower voltage brackets. Although this advantage is particularly pronounced at 250–300 volts, the Excitron rectifier is nonetheless equally adaptable for use at higher voltages.



Small Diameter Switchboard Wire.—To permit fast, neat installations, a new "Deltabeston" switchboard wire insulated with purified asbestos and plasticized polyvinyl chloride compound of the type used in "Flamenol" wire, has been announced by the General Electric appliance and merchandise department, Bridgeport, Conn. The reduction in overall diameter size of the new wire is particularly marked, with No. 12 wire, for one example, having been reduced from the standard size of .225 inches to .195 inches. Reductions for other wire sizes are proportionate. The new G-E Deltabeston switchboard wire is extremely flexible and very light. Insulation will not break or crack at bends. A paper separator between the copper and the insulating wall permits clean, quick stripping. The wire is approved by Underwriters Laboratories for temperatures up to and including 90 degrees Centigrade.

A complete list of Standards of the AIEE appears on the back cover of the 1939 Yearly Index, bound separately and accompanying this issue.

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Bare Wire and Strand—pigtail, braided copper, trolley

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Building Wires
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Power Cables
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Parkway Cables,
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Telephone Wires and Cables

And a wide variety of other wires and cables, either Standard or to Customer's Specifications

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Prompt Service is available at all offices and warehouse points listed below, where large stocks of a wide variety of standard Roebling Wires and Cables are always on hand. Your request for information, prices or samples will be welcomed.

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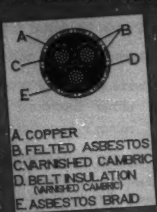
This cable, built for a particular central station application, answers four demands.

1. It permits high current densities necessary during peak load periods.
2. It resists extreme ambient temperatures.
3. Insulation is flame-proof—isn't damaged by severe treatment.
4. Interlocking armor eliminates need for rigid conduit installation.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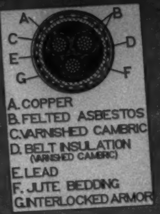
A. COPPER
B. FELTED ASBESTOS
C. VARNISHED CAMBRIC
D. BELT INSULATION (VARNISHED CAMBRIC)
E. ASBESTOS BRAID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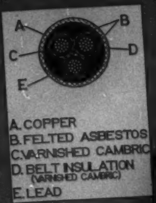
E. LEAD
F. JUTE BEDDING
G. INTERLOCKED ARMOR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B. FELTED ASBESTOS
C. VARNISHED CAMBRIC
D. BELT INSULATION (VARNISHED CAMBRIC)
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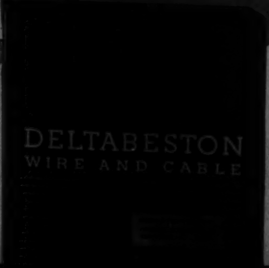
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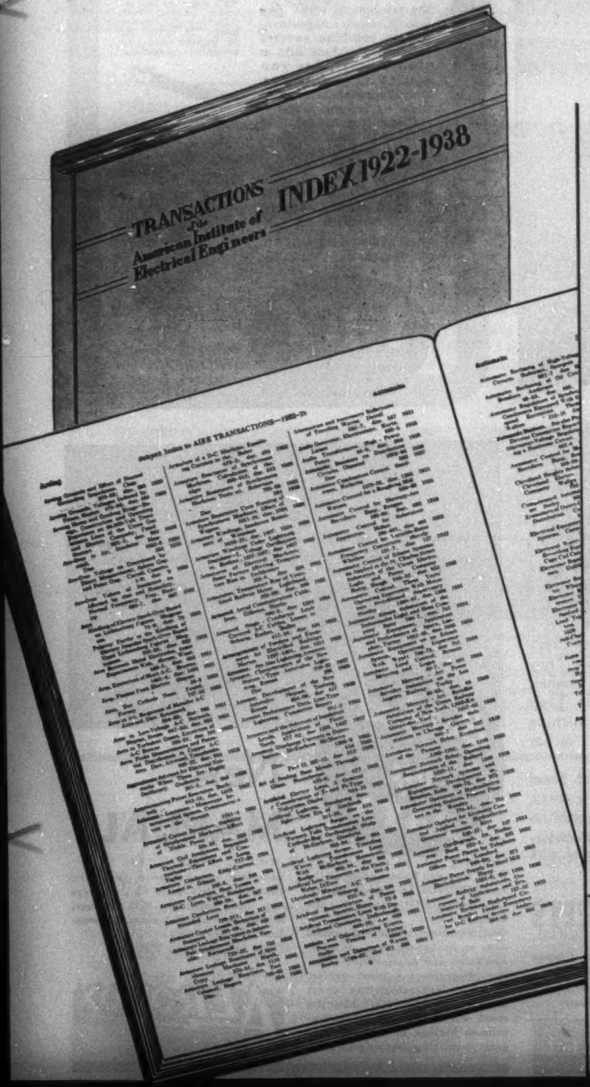

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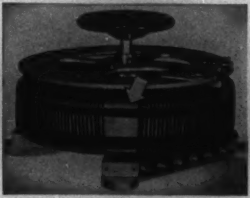

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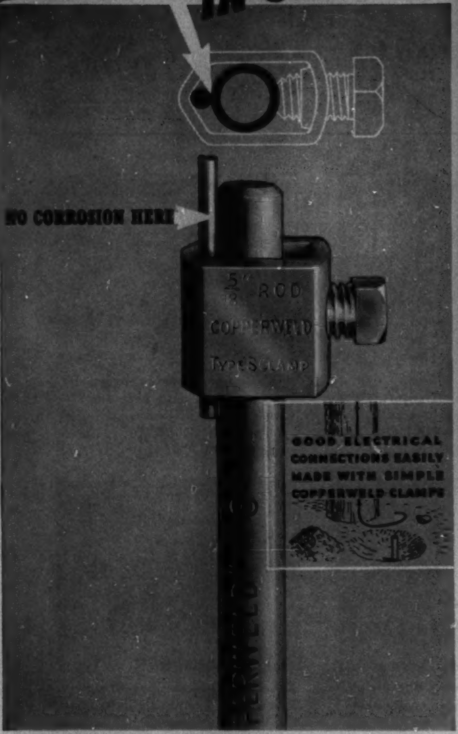
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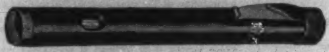

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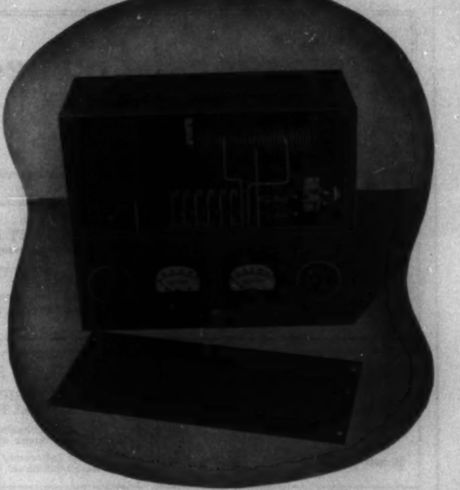

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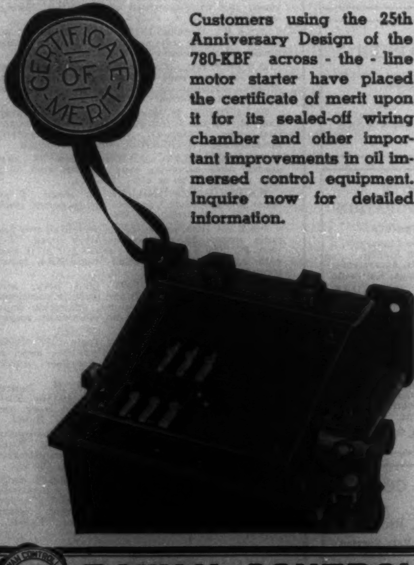

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- **RHEOSTATS, LABORATORY**
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    - General Cable Corp., New York
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    - Kerite Ins. Wire & Cable Co., New York
    - National Elec. Products Corp., Pittsburgh
    - Okonite Company, The, Passaic, N. J.
    - Roebling's Sons Co., John A., Trenton, N. J.
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    - General Cable Corp., New York
    - General Electric Co., Bridgeport, Conn.
    - National Elec. Products Corp., Pittsburgh
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    - Roebling's Sons Co., John A., Trenton, N.J.
  - *Bare Copper*
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    - Copperweld Steel Co., Glassport, Pa.
    - Crescent Ins. Wire & Cable Co., Trenton,N.J.
    - General Cable Corp., New York
    - National Elec. Products Corp., Pittsburgh
    - Roebling's Sons Co., John A., Trenton, N. J.
  - *Bronze*
    - Copperweld Steel Co., Glassport, Pa.
  - *Copper Covered Steel*
    - American Steel & Wire Co., Cleveland, O.
    - Copperweld Steel Co., Glassport, Pa.
    - General Cable Corp., New York
  - *Flexible Cord*
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    - Crescent Ins. Wire & Cable Co., Trenton,N.J.
    - General Cable Corp., New York
    - General Electric Co., Schenectady, N. Y.
    - National Elec. Products Corp., Pittsburgh
    - Okonite Company, The, Passaic, N. J.
    - Roebling's Sons Co., John A., Trenton, N. J.
  - *Heavy Duty Cord*
    - American Steel & Wire Co., Cleveland, O.
    - Crescent Ins. Wire & Cable Co., Trenton,N.J.
    - General Cable Corp., New York
    - National Elec. Products Corp., Pittsburgh
    - Okonite Company, The, Passaic, N. J.
    - Roebling's Sons Co., John A., Trenton, N. J.
  - *Lead Covered (Paper and Var. Cambric Ins.)*
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    - General Cable Corp., New York
    - General Electric Co., Schenectady, N. Y.
    - Kerite Ins. Wire & Cable Co., New York
    - National Elec. Products Corp., Pittsburgh
    - Okonite Company, The, Passaic, N. J.
    - Okonite-Callender Cable Co., Passaic,N. J.
    - Roebling's Sons Co., John A., Trenton, N. J.
  - *Magnet*
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    - Crescent Ins. Wire & Cable Co., Trenton,N.J.
    - General Cable Corp., New York
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    - Crescent Ins. Wire & Cable Co., Trenton,N.J.
    - General Cable Corp., New York
    - General Electric Co., Schenectady, N. Y.
    - Kerite Ins. Wire & Cable Co., New York
    - National Elec. Products Corp., Pittsburgh
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    - Kerite Ins. Wire & Cable Co., New York
    - Okonite Company, The, Passaic, N. J.
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  - *Weatherproof*
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    - General Cable Corp., New York
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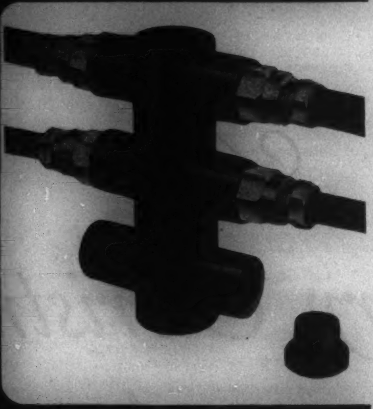

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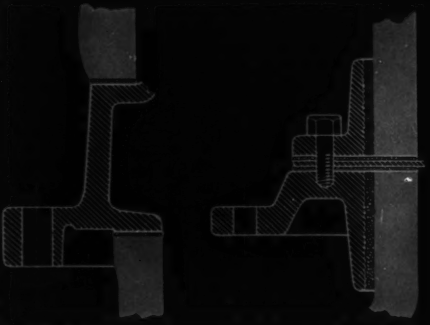

One example of a simplified yet greatly improved detail. Present O-B joints (left) are free of cement and are self-tightening. The old mounting flange (right) was cemented to the porcelain casings and had to be tightened manually.

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Electrical Engineering

TRANSACTIONS SUPPLEMENT

1939

Published by the American
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33 West 39th Street, New York, N. Y.

FOREWORD

¶ This special supplement to Electrical Engineering for 1939 contains pages 675 to 914, inclusive, of the 1939 AIEE Transactions, volume 58, preprinted in this form from the annual volume for the convenience of members who do not subscribe to the Transactions.

¶ The 674 pages of Transactions material preprinted in the segregated Transactions sections of the 12 issues of Electrical Engineering for the year 1939, together with the contents of this supplement, comprise the *complete* content of technical papers and discussions in the 1939 Transactions. Because of the continued effects of the transition from the former to the new publication policy, the content of this volume is somewhat less than normal.

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The Submarine-Cable Plow

C. S. LAWTON
NONMEMBER AIEE

A METHOD of protection of submarine cables by placement "underground" was described during the process of its development in an article[1] written for Electrical Engineering in May 1938. The work then projected has since been successfully carried out, and the first cables scheduled to be plowed under, to protect them from being fouled by fishing gear dragged along the ocean bottom by steam trawlers, have been laid and buried in trenches to a depth of from half a foot to approximately two feet. In the latest operations, sections of cable 25 nautical miles (of 6,087 feet) in length have been dropped into a continuous furrow cut in the ocean bottom, from 500 to 2,700 feet below the surface of the sea. It is the purpose of this paper to describe the engineering features of the entrenching operation, and in a companion paper[2] will be found a description of a device, the submarine-cable depthometer, by which is measured the depth, in inches below the ocean bottom surface, at which the plowed-in cable actually lies in its trench.

Figure 1 shows the location of Western Union cables in trawling areas, with tabulations of interruptions and faults known to have been caused by trawlers since 1920. In general it will be noted that, if anything, damage has been heavier in the winter months when weather conditions are at their worst for the repair ships. Some of the cables are much more important than others from a traffic standpoint but the trawlers have no respect for that feature. It is estimated that trawler damage has cost all cable companies together as much as $500,000 in some years.

In the past, efforts to combat the damage have been concentrated principally upon the use of heavier and more costly cable, and the elimination of final repair splices, with their attendant bights of excess cable, from dangerous areas. The improvement resulting from these efforts has not been great because of economic limitations, and the practical difficulty of handling much heavier cable in deep water, in the first case; and because of reluctance to disturb cable beyond the limits of any one repair unnecessarily, and the time factor, in the second case. The most widely accepted type of cable for use in trawler areas is armored with ten number 1 Birmingham wire gauge soft iron wires, has an overall diameter of $1^5/_8$ inches, weighs 9 tons (of 2,240 pounds) per nautical mile in air or about 6.2 tons per nautical mile in sea water, and has a tensile strength of 20 tons. Many but not all of the interruptions and faults cited have occurred in this type of cable, the manufactured cost of which is about $2,000 a nautical mile.

For many years it had been jokingly said that some day the cables would have to be plowed under, but so far as is known, an American company was the first to give the idea the serious consideration it deserved, the attitude finally adopted being that although it always had sounded fantastic, nevertheless if successful it offered advantages too great to be passed up any longer without at least an effort being made to determine whether it was practicable.

Procedure

In order not to interfere with the operation of a working cable until the last possible moment, the procedure agreed upon for trenching was as follows: the ground would be explored in the vicinity of the existing line across the dangerous area for bottom as free as possible from irregularities, rocks, or other obstructions, and lowest possible towing resistance. A route would be chosen approximately parallel to the existing cable, and an independent section of cable would be buried along it, with both ends buoyed well clear of the vulnerable stretch. After thorough testing to verify that the section had been properly buried, the working cable would be cut on both sides of the vulnerable length and joined through on the buried section, the original length thus removed from circuit then being recovered, and if its condition justified it, repaired and made available for future use.

It soon was decided that the trenching and laying must be done as one operation. From a consideration of the weight and volume of cable to be handled in a single crossing of the trawler grounds it was also evident that the required amount could not be accommodated on the plow itself, but would have to be paid out from the ship's tanks through the plow as it progressed, it being essential not to interrupt the operation from start to finish if the trench were to be continuous.

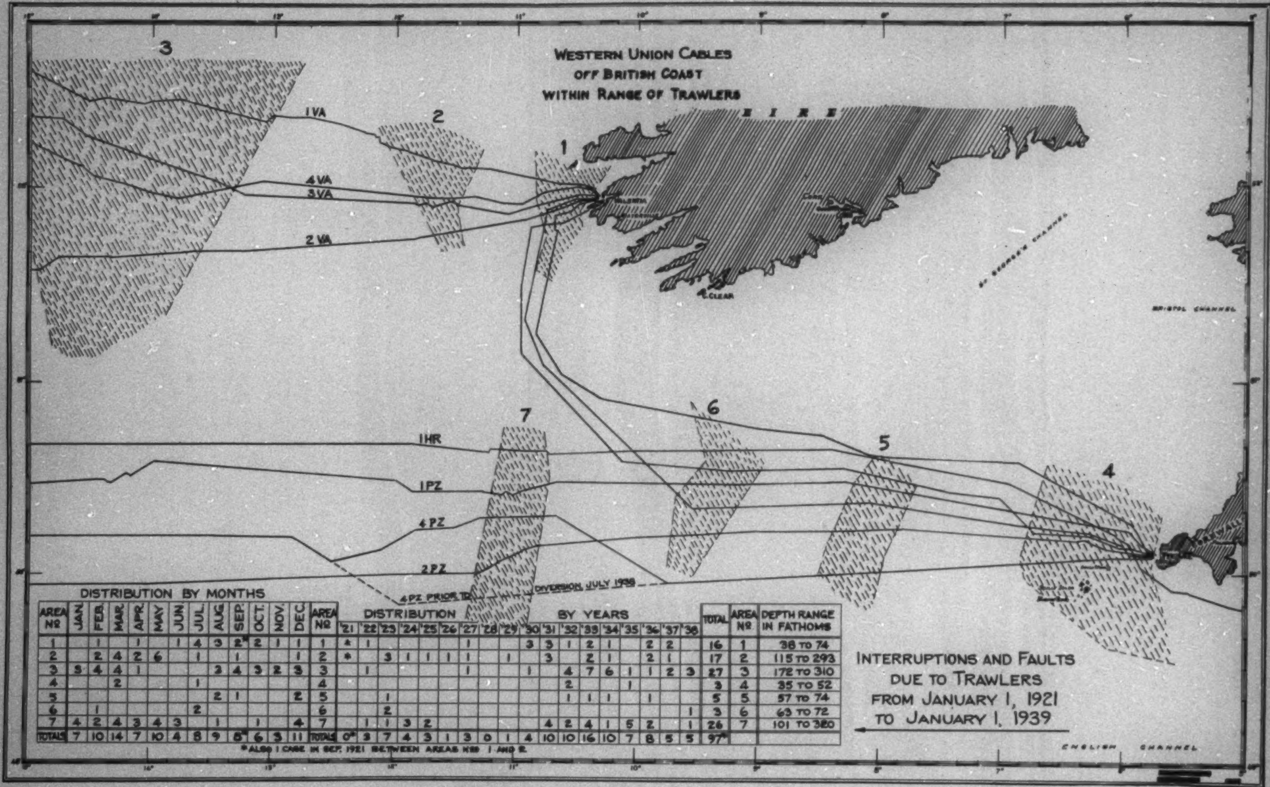
Early Trials

Due to urgency of the matter, the first experiments in 1934 were conducted with plows which while incorporating the basic principles,[3] nevertheless were built from preliminary designs before there had been a real opportunity to come to grips with the technical problem and before the mechanics could be fully mastered. From these experiments much valuable information was obtained, however, which probably could not have been gathered in any other way. As the ship was to operate off the Irish coast it was decided to construct the plows in England, but in the intervals while the ship was proceeding to England and the plows were being built, a one-fourth-scale working model was constructed in the laboratory in the United States and tried out on a nearby beach. Wire rope was stretched along the ground under water to simulate cable and was buried by the model in both sandy and muddy bottom. The model dug in quickly but showed a tendency for the stern to lift a little when handling cable with much tension on it. Tension was important because in order to pass long lengths of cable through the plow in one uninterrupted operation, it was imperative that no slack accumulate ahead which would lead to a foul, and the only sure way of avoiding slack was to keep plenty of tension on the cable. The effect of the elevation of the towing position on the tendency for the stern to lift was obvious, and in an attempt to bring this force into more nearly horizontal alignment with the center of ground resistance, the towline was shackled directly to the vertical guard plate below ground level, a thin flat-bar link being used on edge to cut through the ground ahead. Fins at various angles were tried on the sides of the share to grip the ground on each side but these were of doubtful assistance in holding the rear down and were finally abandoned altogether. The towing tension for the model without cable was about 150 pounds. When burying wire rope on which 50

Paper number 39-54, recommended by the AIEE committee on communication, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 5, 1938; made available for preprinting December 30, 1938.

C. S. Lawton is assistant ocean cable engineer, The Western Union Telegraph Company, New York, N. Y. He designed the present plow and for the past three years has been in charge of the engineering development work on the European side.

[1] For all numbered references, see list at end of paper.


WESTERN UNION CABLES
OFF BRITISH COAST
WITHIN RANGE OF TRAWLERS
EIRE
1
2
3
4
5
6
7
1VA
4VA
3VA
2VA
1HR
1PZ
4PZ
2PZ
4PZ PRIOR TO DIVERSION JULY 1938
ST. GEORGE'S CHANNEL
BRISTOL CHANNEL
ENGLISH CHANNEL
C. CLEAR
14°
13°
12°
11°
10°
9°
8°
7°
6°
5°

INTERRUPTIONS AND FAULTS
DUE TO TRAWLERS
FROM JANUARY 1, 1921
TO JANUARY 1, 1939

DISTRIBUTION BY MONTHS

AREA Nº	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
1		1		1		1	4	3	2*	2	1	1
2		2	4	2	6		1		1			1
3	3	4	4	1				3	4	3	2	3
4			2				1					
5								2	1			2
6		1					2					
7	4	2	4	3	4	3		1		1		4
TOTALS	7	10	14	7	10	4	8	9	8*	6	3	11

DISTRIBUTION BY YEARS

AREA Nº	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	TOTAL	AREA Nº	DEPTH RANGE IN FATHOMS
1	*	1					1			3	3	1	2	1		2	2		16	1	38 TO 74
2	*		3	1	1	1	1		1		3		2	1		2	1		17	2	115 TO 293
3		1					1			1		4	7	6	1	1	2	3	27	3	172 TO 310
4												2			1				3	4	35 TO 52
5			1									1	1	1		1			5	5	57 TO 74
6			2															1	3	6	63 TO 72
7		1	1	3	2						4	2	4	1	5	2		1	26	7	101 TO 320
TOTALS	0*	3	7	4	3	1	3	0	1	4	10	10	16	10	7	8	5	5	97*		

* ALSO 1 CASE IN SEP. 1921 BETWEEN AREAS NOS 1 AND 2.

Figure 1. Location of trawling areas off British coast

pounds tension was held, the towing tension was increased by about 10 pounds. Although the sliding friction was rather high, rollers or other moving parts to assist the passage of the cable were looked upon with some disfavor, because of the presence of so much sand and grit and the liability that they would be put out of action.

The full-scale trials took place on a wet sandy beach on Bigbury Bay, near Plymouth, England, with horses and a tractor to furnish pulling power. The first plow tried embodied modifications by the ship's personnel to the original design for the purposes of increasing the full digging depth (from 12 inches to 19 1/2 inches, it being felt that 12 inches was insufficient on uneven ground), decreasing the frictional resistance of the cable (by introduction of a roller aft), and eliminating all possibility of the plow's remaining in a capsized position when landed on the bottom (by introduction of hoops over the top). The width of the cable trunk and consequent width of share were also increased as a precaution against broken wires and rucked-up outer-serving which might cause blocking of the passageway and jamming. The same dynamic characteristics noted with the model were exhibited by this plow, which dug a 14-inch to 18-inch depth of trench and developed 110 hundredweights towing tension. (This is the British hundredweight of 112 pounds.) Efforts to back-fill the trench were soon abandoned because the scrapers tended to lift the stern of the plow and because they were felt to be ineffectual and unnecessary due to the silting action of sand under water.

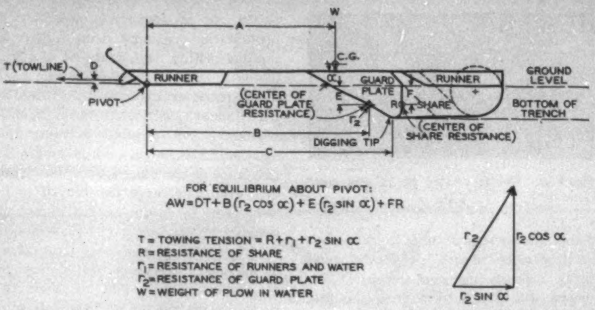

W
A
C.G.
T (TOWLINE)
D
RUNNER
GUARD PLATE
RUNNER
GROUND LEVEL
α
E
F
R
SHARE
PIVOT
(CENTER OF GUARD PLATE RESISTANCE)
r_2
BOTTOM OF TRENCH
(CENTER OF SHARE RESISTANCE)
B
DIGGING TIP
C
FOR EQUILIBRIUM ABOUT PIVOT:
AW=DT+B(r_2 cos α)+E(r_2 sin α)+FR
T = TOWING TENSION = R+r_1+r_2 SIN α
R = RESISTANCE OF SHARE
r_1 = RESISTANCE OF RUNNERS AND WATER
r_2 = RESISTANCE OF GUARD PLATE
W = WEIGHT OF PLOW IN WATER
r_2
r_2 COS α
r_2 SIN α

Figure 2. Mechanics of the plow

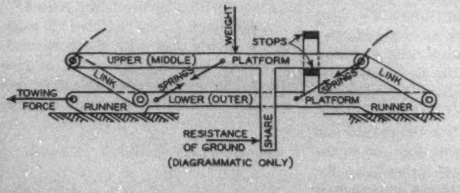


Figure 3. Diagram of automatic trench depth adjustment mechanism

No trials had been made yet on hard bottom, and with the emphasis being placed on the necessity for weight aft to keep the stern down, the matter of unit bearing pressure on the digging tip was given scant consideration. This tip was well forward in the early designs, so that with the upward component of tension bound to develop in towing from a ship, there was not much encouragement for the tip to penetrate hard bottom. It soon became evident that the mechanics of the plow required further study; also that through the use of models the desired information could be collected in a much shorter time and at much less expense than with full-sized plows.

Model Experiments

Space does not permit going into the experiments in detail, but as the conclusions dictated subsequent plow design they deserve to be mentioned. Briefly they were as follows, after 255 trials:

1. The displacement of material caused by the passage of the share does not obey the laws of streamline flow as in the case of fluids. The shape of entrance has little effect upon the resistance encountered. Over 60 model shares were tested, including square, half-round, and streamlined noses, and entrance angles in five steps from vertical to 22 1/2 degrees with horizontal.

2. Shares having small entrance angles with the horizontal give no reduction in towing resistance and do not retain their full grip in the ground unless heavily weighted. Therefore it is not safe to rely upon any shape of share to keep the plow in the ground, as a substitute for dead weight. A vertical entrance gives the smoothest tension graph.

3. Attempts to turn a furrow as on land do not succeed under water. Most of the material is forced aside, even with scoop-shaped shares.

4. Due to the flat deck plate, plows with their center of gravity aft will volplane at very moderate speeds, and once started will continue volplaning at lesser speeds.

5. The best weight distribution is with the center of gravity slightly forward of the digging tip because of (4) and also because on making bottom the plow will settle down on the digging tip and the two forward runners, in which position it is ready to penetrate hard ground in the same manner as an old-fashioned anchor resting on one fluke and its stock.

6. With a plow heavy enough to keep a vertical-entrance share digging properly, there will be enough weight to keep the cable from lifting the stern, even if the center of gravity is placed according to (5).

7. Resistance obeys no infallible law, varying widely in the same material with the same share. If the share is kept in the ground, speed of towing has no appreciable effect on resistance. In very hard bottom the relation between width of share and resistance is almost linear whereas in very soft bottom a reduction of 50 per cent in width is not accompanied by any noticeable reduction in resistance. Therefore a narrow share gives a steadier tension graph through different kinds of bottom than a wide share. Resistance usually varies about as the 3/2 power of the depth, but in some cases it varies more like the square. More experiments are necessary before these relationships can be definitely established. When expanding any one design to scale the resistance seems to go up about as the cube of the linear dimensions and this ties in well with investigations undertaken a few years ago on the holding power of anchors.[4]

8. Shares with parallel sides cause the material to be displaced along a fault line perhaps 30 degrees from horizontal and to leave mounds to either side which are roughly triangular in shape, their combined cross-sectional area being equal to the area of the trench below normal ground level. After passage of the share the material gradually, but not immediately in clay or hard bottom, slips back into place, covering the trench. Tidal action greatly assists this of course. No observations were possible in locations entirely free from tidal influence.

Figure 2 shows the elements of a cable plow in contact with the ground. Runners are attached to a deck plate. The share is a long steel casting cored out to

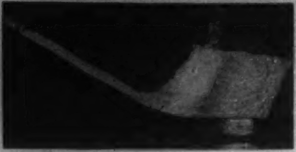


Figure 4. Stellite overlay on tip and guard plate

permit the passage of cable to and underneath an after "sheave" or grooved wheel which rolls it into the trench. (This sheave was a departure from the first design as in spite of probable bearing difficulties it was felt to be necessary to relieve the friction on the cable as much as possible.) Ahead of the share and welded to it is the triangular guard plate which protects the digging tip and allows the share to surmount obstructions. Naturally a good design aims not at equilibrium but at a safe margin in the factors on the right-hand side of the first equation. For weight distribution as recommended in (5) dimension *C* must exceed *A*, and as the lever *A* determines the effectiveness of the weight it is easy to see why a plow must be both long and heavy.

Design of Present Plow

Indications from the model experiments were that it would be unwise to design a plow for a trench depth beyond ten inches because of the anticipated maximum towing tensions. However, it was felt that the need for a deep trench was not as great in hard ground as in soft and that a way might be worked out to let the depth of trench vary automatically with the consistency of the ground, thus leveling off the towing tension. (The above figure of ten inches was based on the types of bottom available for model work, which were many but naturally did not extend much beyond low water mark.) This was accomplished by constructing the plow in two parts linked together like members of a parallel rule,[5] the middle part, corresponding to the upper member of the rule when set in a vertical plane, carries the share and cable guides. The outer part, corresponding to the lower member of the rule, carries the runners and towing lugs. Resisting the link motion and tending to keep the two parallel parts together are four helical tension springs, two of which are mounted so as to be adjustable (figure 3).

When the ground resistance reaches a predetermined maximum, the springs become active, allowing the middle part to swing aft and up, thus lifting the share partly out of ground as necessary to prevent the resistance rising further, if possible within the limits of the link motion. In the present plow the maximum trench depth below the bottom of the runners is 16 inches and automatic adjustment is possible between this figure and 8 inches at a maximum ground resistance of 255 hundredweights. However even this range has proved to be insufficient to ensure against higher resistances as at times a resistance of over 300 hundredweights has been encountered in digging a trench 8 inches deep by $4^{1}/_{4}$ inches wide. This is about the minimum practicable width, as allowing for $^{3}/_{4}$-inch walls the cable trunkway is but $2^{3}/_{4}$ inches wide, which leaves only $^{1}/_{2}$-inch clearance for the cable at splices.

Figure 4 shows a close-up view of the digging tip and guard plate. The abrasive wear has been so severe that only recently have we been able to protect the tip and plate edge well enough for them to survive one operation. This has been accomplished by streamlining the tip, not to reduce the towing resistance, but to spread the wear over a greater area, thus reducing unit bearing pressure, and by grinding the plate edge to a 15-degree double chisel edge, then applying number 1 grade stellite to the wearing surfaces.

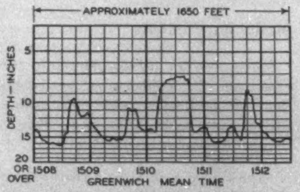


Figure 5. Extract from penetration record for 1HR cable, showing net depth of trench below normal ground level

The runners are made with a narrow tread so that when the plow passes into really soft bottom where the resistance can be counted upon to ease off considerably, they will sink into the ground and allow the deck to settle down on to the mud. With runners 12 inches below the deck the maximum depth of trench is thus increased to something approaching 28 inches. This figure is probably unattainable because of the mound thrown up beside the share which would keep the deck from settling down to normal ground level.

The way in which the variable depth feature functions in actual practice is illustrated by the graph in figure 5, an extract from the record taken last summer (1938) while burying the Western Union 1*HR* direct Paris cable across number 7 trawling area. The means for obtaining this and other records will be described later.

To pass cable through the plow with minimum tension on it and yet to avoid the possibility of slack occasionally creeping in necessitates some means of measuring the cable tension at the plow, as the formula in use for computing residual tension is not sufficiently accurate, the conditions at the ship cannot be held sufficiently uniform, nor can the ship be controlled with sufficient exactness to rely otherwise upon anything but a large margin of safety. It was therefore decided to incorporate a cable dynamometer[6] in the design of the present plow. This takes the form shown in figure 6, and utilizes the offset in the cable line required to place it below ground level by measuring the reaction on a grooved sheave over which the cable takes a bend of 36 degrees.

At the same time it is required to know whether cable is sinking to the bottom ahead of the plow or whether the plow is pulling the cable down forcibly. A pivoted inverted-U-shaped member arranged to swing over the forward cable bellmouth and counterweighted in such a way as to cause it to seek the vertical bears lightly against the underside of the cable, changing its angular position to accommodate itself to the elevation of the cable entering the bellmouth. This is called the "cable feeler."[7]

For measuring the depth of trench, or penetration, a weight is trailed along on the end of a rod free to swing in a longitudinal vertical plane. The weight rides along on the ground beside the share. It changes its angular position to accommodate itself to changes in elevation of the share with reference to the ground.[8]

A pendulum is used to record the angle of the plow's deck with the horizontal. It swings longitudinally so as to give slopes of ground traversed, also to furnish a useful check on the penetration gauge.

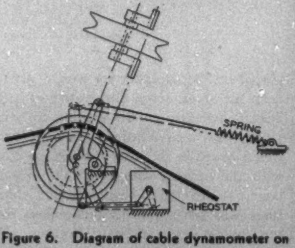


Figure 6. Diagram of cable dynamometer on plow

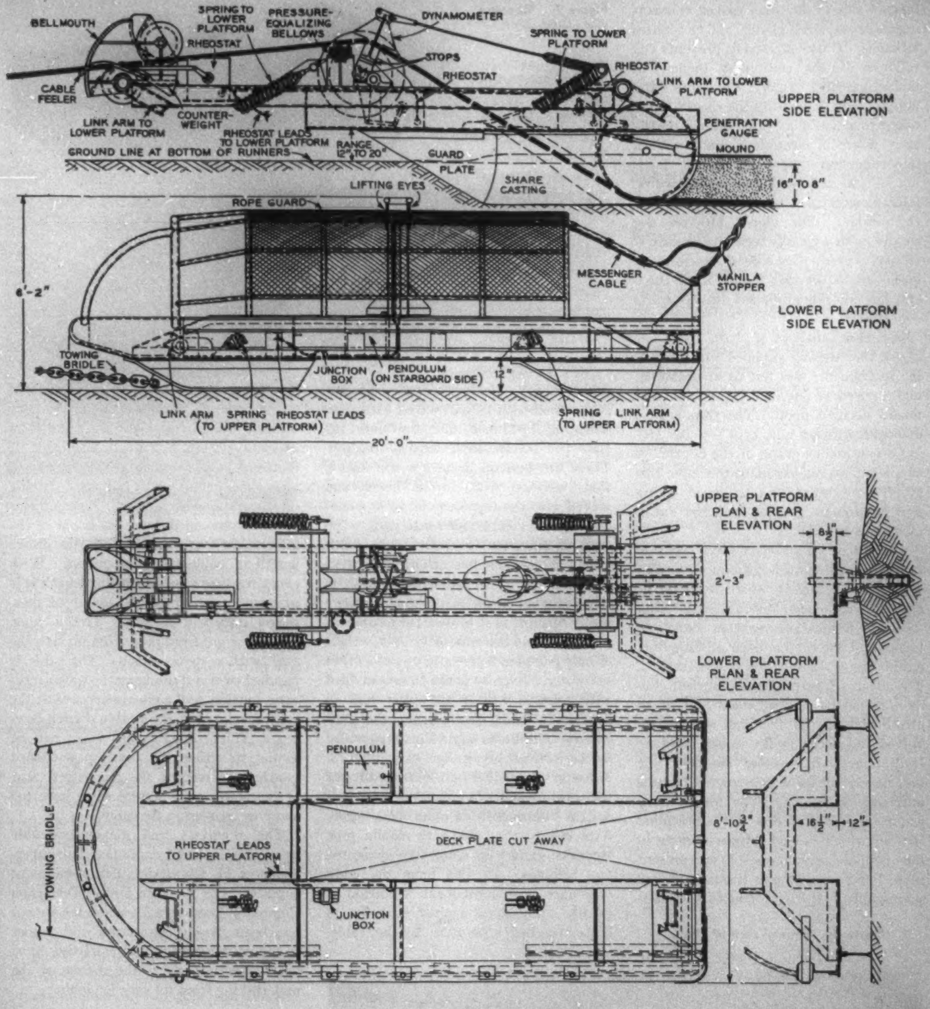

BELLMOUTH
SPRING TO LOWER PLATFORM
PRESSURE-EQUALIZING BELLOWS
DYNAMOMETER
RHEOSTAT
STOPS
RHEOSTAT
SPRING TO LOWER PLATFORM
RHEOSTAT
LINK ARM TO LOWER PLATFORM
UPPER PLATFORM SIDE ELEVATION
CABLE FEELER
LINK ARM TO LOWER PLATFORM
COUNTER-WEIGHT
RHEOSTAT LEADS TO LOWER PLATFORM
RANGE 12" TO 20"
PENETRATION GAUGE
MOUND
GROUND LINE AT BOTTOM OF RUNNERS
GUARD PLATE
SHARE CASTING
16" TO 8"
LIFTING EYES
ROPE GUARD
6'-2"
MESSENGER CABLE
MANILA STOPPER
LOWER PLATFORM SIDE ELEVATION
TOWING BRIDLE
JUNCTION BOX
PENDULUM (ON STARBOARD SIDE)
12"
LINK ARM
SPRING
RHEOSTAT LEADS
(TO UPPER PLATFORM)
SPRING
LINK ARM
(TO UPPER PLATFORM)
20'-0"
UPPER PLATFORM PLAN & REAR ELEVATION
8½"
2'-3"
LOWER PLATFORM PLAN & REAR ELEVATION
PENDULUM
TOWING BRIDLE
RHEOSTAT LEADS TO UPPER PLATFORM
DECK PLATE CUT AWAY
8'-10¾"
16½"
12"
JUNCTION BOX

Figure 7. General arrangement of plow

Damping is necessary to iron out shocks and jerks incidental to the plow's motion. It is accomplished by having the pendulum submerged in a special heavy grade of castor oil.

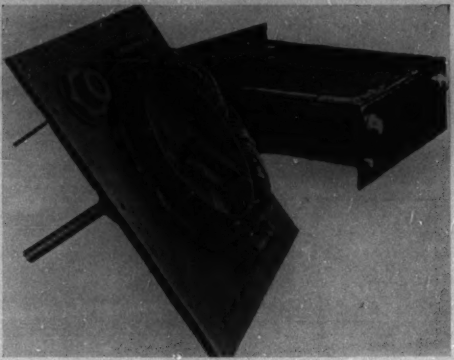
A drawing and photograph of the completed plow are shown in figures 7 and 8. The superstructure is designed to keep the various lines from fouling the plow while lowering and getting under way.

The angular motions of the cable dynamometer, cable feeler, and penetration gauge are transmitted to rheostat arms through linkages, whereas the pendulum rheostat is mounted on the same shaft and in the same container as the pendulum itself.

Telemetric System Between Plow and Ship

The operation of rheostats under hydrostatic pressures up to 1,200 pounds per square inch presented a few difficulties which however were successfully overcome by enclosing the units in containers filled with castor oil, chosen because it is not injurious to rubber insulation and has a reasonably low coefficient of compressibility. The containers communicate with a central bronze bellows also filled with castor oil and with enough capacity to absorb the volume changes caused by the hydrostatic pressure. Transmission of the external pressure to the interiors of the containers equalizes the pressure on each side of the cover gasket, connecting cable and shaft glands, and eliminates leakage. It also effectively prevents the collapse of the containers themselves under pressure. Figure 9 illustrates the design. The leads from the rheostats are taken to an oil-filled junction box on the plow where connection is made with a four-conductor "messenger cable" leading to the ship and to four recording milliammeters and ballast resistances on the bridge. The ship's 110-volt d-c supply, with a voltage regulator to keep it steady, is used. One side of the circuit is grounded to the ship's hull. Each rheostat has one side grounded directly to its container.[9]

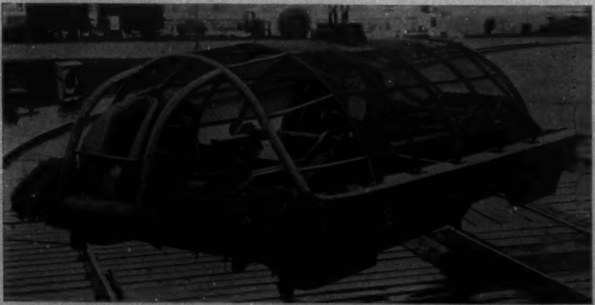
Figure 9. Rheostat and container



For close analysis a chart speed far above that usually supplied with recording instruments was felt to be desirable, and a speed of one inch per minute was finally decided upon. The ship is also equipped with an echo-type sounder giving a continuous graph of the depth. A simple alteration was made to enable this graph to be run at the same speed, giving five continuous graphs over the entire plowing operation.

The use of a messenger cable separate from the plow towline introduced a complication in handling which it would be desirable to avoid, but although other means of transmission such as sound impulses and radio have been investigated, a cable seems the only practicable method. The idea of incorporating electrical conductors in the towline itself had to be abandoned due to the high stresses involved and necessity for almost constant readjustment in towline length. The first messenger cable constructed became unreliable after very little use in deep water apparently due to vibrational stresses which caused fatigue failures in the copper conductors. The present cable has gone through the past season successfully. It has conductors of cadmium copper. Each insulated conductor is sheathed with 26 galvanized hard-steel wires of 0.022-inch diameter and 100 tons per square inch tensile strength. These are laid up around a coir heart, then wormed with tarred hemp, and served with compounded cotton tape and one layer of compounded jute yarn. The over-all diameter is about three-fourth inch. The cable has an ultimate tensile strength of 83 hundredweights. It is as near to being in torsional balance under tension as it is possible to make a cable and has the extremely light weight of only one pound per fathom (six feet) in sea water. Even so it has to be provided with buoyancy near the plow end to prevent its being run over by the plow when getting underway. This is provided in the form of two groups of eight-inch-diameter alloy-steel ball floats made for the trawling industry and sewed up in long canvas "sausages" of nine balls each. Attached to the cable with manila rope stoppers, they trail along like elongated toy balloons. In this form the eddy resistance and consequent vibration is greatly reduced as against that for 18 balls attached separately to the cable. The messenger is made in one length of 2,000 fathoms because splicing is very difficult due to its construction, and if an accident occurs by which the cable is damaged it is essential to have plenty of spare uninterrupted length after cutting off the damaged portion. The surplus cable is kept coiled down flat in one of the after cable tanks on the ship, the entire length of cable being in circuit. With every readjustment in towline length it is necessary to readjust the length of messenger outboard to suit. This is done by paying out from or picking up into the tank with a steam winch. The cable is handled over a dynamometer which indicates tension, and passes overboard at the stern from a special portable derrick having a 20-foot steel boom which can be swung to either the port or starboard quarter for keeping the messenger clear of the ship's twin screws when lowering away or recovering the plow.

Figure 8. General view of plow



The rheostats and messenger cable were manufactured under the close supervision of H. Kingsbury, European plant engineer, The Western Union Telegraph Company, London, with whom the author has been closely associated and whose technical knowledge and initiative have contributed greatly to the success of the undertaking from its very beginning.

Lowering the Plow

The plow itself weighs about 180 hundredweights in air. It is handled from the forward well deck by one of the foremast derricks specially reconstructed to give greater outreach and equipped with its own steam winch. The whole gear was tested to 400 hundredweights before being used. A strong line is taken from the forward hold, over one of the twin sets of cable gears, thence over one of the bow sheaves and along the outside

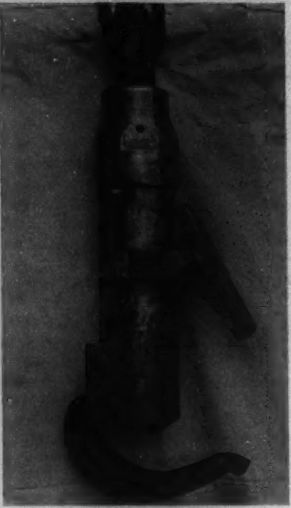


Figure 10. Releasing gear

of the ship to the well deck where it is made fast to a special attachment on top of the plow. The derrick purchase is also made fast to the same attachment and serves to lift the plow (with towline and messenger cable also attached) over the bulwark and lower it about 20 fathoms over the side. Picking up then commences on the other line (and towline) which brings the plow up transversely under the ship's overhanging bow platform and headed to port. The derrick line is next unshackled and the plow is in position for lowering to the bottom.

While still on deck a rope strop has been reeved through the cable passageway in the plow and its two ends shackled together. With the plow under the ship's bow the strop is unshackled and the end passing into the forward end of the plow is joined onto a rope passing over one of the three large bow sheaves, over the other cable paying-out gear and down to one of the cable tanks where it is spliced to the cable end. Previous to the commencement of operations a mushroom anchor has been planted with a length of heavy ground chain at the position where the tow is to commence. A buoy is moored to the tail of the mushroom to facilitate subsequent recovery. Another buoy is moored to the end of the laid-out chain. The ship now steams slowly up to the latter buoy, takes it aboard, transfers its moorings to the after end of the strop through the plow, and drops the mooring overboard. The ship's head is swung into position 90 degrees clockwise from the course to be followed, and the plow is ready for lowering.

A special form of releasing gear[10] which would not release the plow when the ship's head dropped suddenly on the swell had to be designed, as the ordinary form lets go immediately upon relief of tension, and the plow with its large deck area sometimes cannot sink quite as fast as the ship is liable to drop it, when the lowering rate is compounded on the swell motion. This apparatus (figure 10) contains a hydraulic cylinder and plunger working somewhat like a door-closer. After release of tension a compression spring forces the plunger slowly down while a needle valve governs the rate of escape of the water therefrom. Resumption of tension before the plunger has completed its travel immediately returns the plunger to its initial position by recompressing the spring, a foot-valve in the cylinder opening to permit re-entrance of water. If tension is not re-established before completion of the plunger travel, this being the period for which the device is set, the plunger throws a trigger and opens the tumbler hook. The period is set by adjusting the needle valve. Ten seconds has been found to be satisfactory. After the plow has landed on bottom and the required ten seconds have elapsed, the lowering line and releasing gear are hove back on board.

While lowering the plow it is essential that ship and plow do not change their relative headings by as much as 180 degrees, for in that event the plow may be swung around in a complete circle upon the commencement of towing. If this happens, the cable will have a turn around the towline and the foul cannot possibly be eliminated except by recovering the plow. For this reason we prefer to lower away at the shallow end of the job, usually in about 90 fathoms, also because the towline with which the ship gets underway is shorter at this end and it is easier to pay away chain than to pick it up under high stress in readjusting the length with changes in depth of water.

Keeping Cable Clear

To provide a good spread between cable and towline at the top, as soon as the plow has been landed on bottom the cable-end rope is transferred aft along the starboard side of the ship to and over a large sheave mounted thereon somewhat abaft amidships, so as to leave the ship at that point instead of the bow. To accomplish this requires that a strop be previously rigged over the side sheave with both ends brought forward. The cable-end rope is parted at a connection and the strop is inserted by joining the rope on to its ends, the lower one of which is then dropped overboard. Following this, the ship swings to course and moving ahead (figure 11) resumes paying out towline and messenger and begins to pay out cable as necessary for the commencement of towing. It should be noted that the plow slides down the cable-end rope rather than the cable itself, which avoids possibility of damage to the cable.

Towing Position

Early in the experimenting the question of the best towing point on the ship came

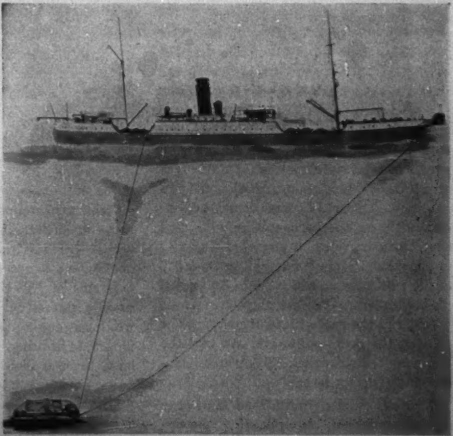


Figure 11. Plow on bottom. Ship paying out towline

up. Contrary to popular impression it is not the stern. When a ship swings, she pivots on a point well forward of amidships. If the stern is held, the rudder is not effective. Cable repair ships are equipped to handle rope and cable over the bow and their powerful cable engines are forward, not aft. It was therefore natural to choose the bow as the towing position.

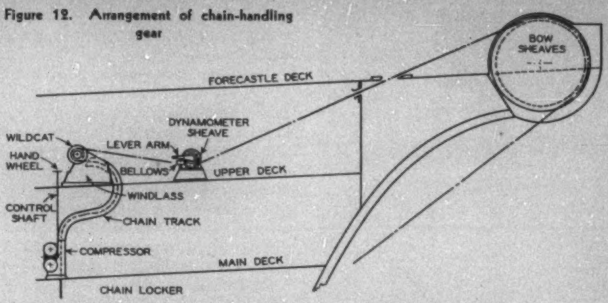
Towline

In order to obtain a horizontal pull at the plow it was obvious that the towline would have to be ballasted. The original arrangement consisted of from 40 to 85 fathoms of $1^{1}/_{4}$-inch ground chain at the lower end, shackled to a steel and hemp grapnel rope. The ship's cable drums are suitable for handling this type of rope under the stresses usually experienced in cable repair work, but they provide only a frictional grip which is insufficient to prevent slippage when paying away under high tensions. Bulky connections in the rope every few hundred fathoms were a constant source of trouble in passing the drum, being apt to take riding turns and lead to slipping and surging which was ruinous to the rope and dangerous for those handling it. The tendency of rope to twist under tension made necessary the use of a special roller-bearing swivel ahead of the chain. The features which finally eliminated rope for towing however, were the fact that chain had to be handled anyway before the plow could be taken back on board, and the limits imposed on the size and therefore strength and weight of rope by the ship's cable drums. The grapnel rope mentioned had a very low factor of safety but was the largest rope which could be accommodated.

A continuous chain for towing has the advantage of more weight to absorb the vertical component of the towing tension, greater springiness due to the curve produced by its suspended weight, freedom from torsional stresses under tension, and practically no restriction upon the length which can be manufactured without connections. Should connections be required they could be more easily handled than those in rope. A more positive grip is provided by the "whelps" or "snugs" of the wildcat over which chain is handled on a windlass. Against these had to be considered the extra lift in recovering the plow at the deep end of the tow and the fact that the ship's windlass was not designed for such a heavy load.

Whereas space limitations and the ship's regular duties prevented the installation of larger cable drums, a more powerful windlass could be and was installed within the existing space. The plow weighs 155 hundredweights in water. The longest lift is in 450 fathoms depth where the vertical leg of chain in suspension weighs 200 hundredweights, giving a maximum total dead load of 355 hundredweights on the windlass and chain. Naturally with the ship responding to a swell, the live load at times raises this much higher. The windlass rating is 400 hundredweights at a speed of 50 feet a minute, which is really slower than desirable, but when the plow is lifted the weight decreases as the chain comes inboard.

Figure 12. Arrangement of chain-handling gear



The chain is one-inch-diameter stud-link made in nickel-steel by the die-lock process in one continuous length of 700 fathoms. It has an ultimate tensile strength of 126,000 pounds (1,125 hundredweights) and was proof-tested to 84,000 pounds (750 hundredweights). It weighs 40,102 pounds in air, or about 0.445 hundredweight per fathom in sea water. It was manufactured at Chester, Pa., under the supervision of E. R. Harrall, who is on the staff of our engineer of lines, New York. The strength/weight ratio is about double that for ordinary one-inch stud-link wrought-iron chain.

Chain Handling

When it came to handling the chain on a wildcat, complications arose. The usual anchor chain is picked up under a relatively small load, as the weight of the anchor and suspended chain is not great in terms of the chain's strength. It is usually payed out on the run with the windlass engine declutched and only moderate braking, whereas in our case we have to both pick up and pay out chain under very heavy loads.

The action of a wildcat is something like that of a chain sprocket on a bicycle except that the grip is on the outside of the links and we are not dealing with an endless chain which, unless it contains slack, cannot ride up out of the sprocket. The ideal cat for picking up under load is not the ideal one for paying out under load, because it is almost impossible to achieve perfect uniformity in the pitch of the links of a long chain.

If two wildcats could be accommodated the ideal design would include one for picking up, which would have the pitch of the pockets slightly greater than that of the links, and another for paying out, with the pitch of the pockets slightly less than that of the links. Unfortunately there was no room for two cats in our case. The best we could do was to exercise great care to make the pitch of the cat exactly right and then clamp down a rigid specification for pitch uniformity in the chain itself. The length over any six links when stressed to the proof load was successfully held to a tolerance of $^{1}/_{16}$ inch, which is about one-tenth the tolerance allowed on an anchor chain of this size by the Navy. As a further safeguard against links riding up out of the pockets of the cat, a special snubbing arrangement was designed, consisting of a curved chain track and multiple compressor installed between the locker and the cat. The whole arrangement is shown in figure 12. A water-cooled brake 40 inches in diameter by 13 inches wide installed on the windlass intermediate shaft has capacity to absorb some 300 horsepower.

The ship's cable dynamometers could not be used with chain passing directly down through the deck to the windlass, and their sensitivity falls away rapidly toward the higher end of their scale making them unsatisfactory for measuring towing tensions anyway. In order to avoid passing the chain through the deck at too small an angle of intersection, a guide sheave had to be introduced ahead of the wildcat. The obvious thing to do was to utilize the reaction of the chain against this wheel, due to its change in direction, to measure tension. To do this, the middle portion of the shaft upon which the wheel turns was made larger in diameter and eccentric to the two ends, like a cam. The wheel is mounted on two Timken tapered roller bearings. The shaft itself is also free in the two end bearings (also tapered rollers) but is keyed to a lever arm extending horizontally to a fulcrum on top of a large bronze bellows mounted on the same cast-steel bracket as the shaft. The offset of the cam center is in the same line with but opposed to the lever arm. Tension on chain passing under the wheel causes an upward reaction on the offset cam and the shaft end bearings, which produces a downward reaction of the lever arm on the bellows. Communicating with the bellows are five pressure gauges, one close by and at practically the same elevation which is used as a monitor, one near the windlass, two back-to-back on the forecastle head, and one on the bridge. The bellows system is filled with a light grade of oil. To calibrate the dynamometer, weights are suspended over the bow on the chain and pressure readings are taken on the monitor gauge. To calibrate the other gauges, pressure is created artificially in the bellows by screwing down on the upper adjustable stop of the lever arm until any desired reading is reestablished on the monitor. The other gauges can then be marked directly in hundredweights tension from the calibration curve of the monitor. A disadvantage is that, except for the monitor, the gauges are all at a higher elevation than the bellows. It follows that when tension is removed from the chain these gauge lines are below atmospheric pressure due to the gravity head which the bellows, being flexible, refuses to support. Very slight air leakage has thus far been unavoidable except by keeping enough pressure artificially on the bellows to maintain all lines above atmospheric pressure. It is possible that an electric repeating system from the monitor gauge could be worked out which would be easier to maintain but thus far no very dependable way of making a direct conversion from hydraulic pressure to electrical readings has been discovered. The fluid displacement in such a system is very small and cannot be greatly increased without interfering with its greatest asset, the practically linear response over the entire range of tensions. The dynamometer is illustrated in figure 13.

To assist in quick determinations of the amount of chain towline required to keep the vertical component of towing tension within a reasonable maximum at the head of the plow, a series of graphs has been prepared, of which figure 14 is a sample, each for a different length of chain. The graphs also indicate the horizontal distance from ship to plow, the amount of chain, if any, on the ground ahead, and the horizontal component of towing tension, all based on the catenary formula. To obtain this information for any length of chain it is necessary only to enter the proper graph with the depth and towing tension at the ship. Small differences in depth between ship and plow are usually negligible, as is the distortion of the catenary curve due to water resistance against the chain at plowing speeds.

Passing Cable Through Plow

If it were possible to maintain the speed of ship and the cable tension at the ship with precision, and if the depth were fairly uniform, the ideal condition for passing cable through the plow would be to so adjust towline length as to keep the plow at the exact distance behind the ship where the cable, sinking at its natural rate, were tending to make bottom. Due to so many variables however, this point is constantly shifting and the towline cannot be controlled with sufficient agility to attempt successfully such a procedure. Cable laid with no more than sufficient tension at the ship to place it on bottom free of residual tension tends to sink in a straight line, the angle of sinking depending upon the speed of the ship. Excess tension at the ship distorts the straight line toward the catenary shape, increasing the length in suspension. For moderate excess tensions the line is still nearly straight, the curvature in the lower portion being only slightly less than that due to inherent stiffness in the cable where it comes tangent to the bottom, and therefore fairly local. If under these conditions the plow is brought up to the ideal or "critical" point of tangency it has to come fairly close before the cable feeler begins to indicate the lifting of the vertical angle of cable approaching the plow. Should the mark be overshot the cable angle rises steeply and there is almost inevitably a bad lead with high friction against the upper part of the bellmouth, requiring immediate corrective action at the ship. Figure 15 illustrates this condition. There is bound to be considerable lag when checking the speed of a ship or changing the shape of a long length of suspended cable, for which reason it is felt safer in the present state of the science to keep the plow a safe distance astern of the critical point, with cable entering the bellmouth from a few degrees below horizontal. By far the greater part of the cable laid last summer (43 miles) was placed on bottom ahead of the plow without any noticeable increase in lead friction from this feature.

It is significant that whereas before the advent of the messenger cable and electrical instruments it was a difficult problem to avoid accumulations of jute and compound, broken wires, etc., which eventually blocked the cable passageway of the plow and terminated the tow, there has been no trouble of this description since.

Residual Cable Tension

Observations made of the plow upon recovery point to the existence of lateral subsurface currents in the areas worked, cable markings almost always showing a tendency for cable to enter the plow bellmouth a bit off the centerline, not always on the same side. This lateral displacement of cable from its natural line cannot be controlled. It results in a certain minimum residual tension in the cable as left by the plow, usually sufficient to eliminate any helical set remaining in the cable from coiling in circular

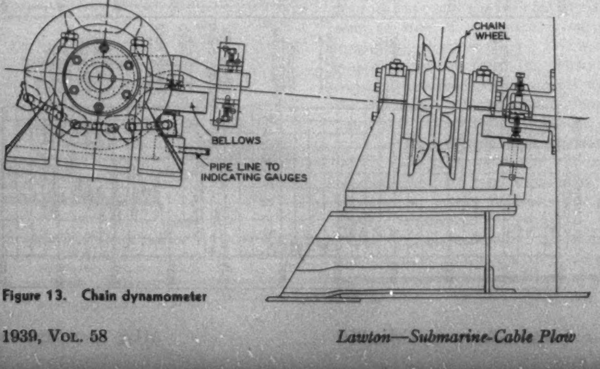


Figure 13. Chain dynamometer

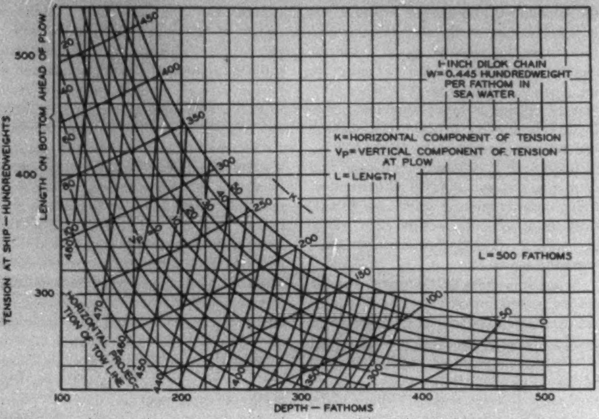


Figure 14. Sample of chain graphs

tanks, but at times the cause of anxiety when passing over irregularities in the ground. The amount of tension left on the cable by the plow is registered on one of the milliammeters. At the same time, ground slopes are registered on another. Records of the ship's speed permit transformation of the time ordinate of the pendulum graph into distance, after which the slopes may be integrated to produce the actual contour of the ground where irregularities have been observed. The penetration graph is then consulted and the bottom of the trench laid off. A scale template of the catenary curve of the cable under the corresponding residual tension laid over the drawing of the trench will at once show whether there has been any suspension of cable across a depression, and if so whether the suspension has been enough to lift the cable out of the trench (figure 16 is a sample irregularity).

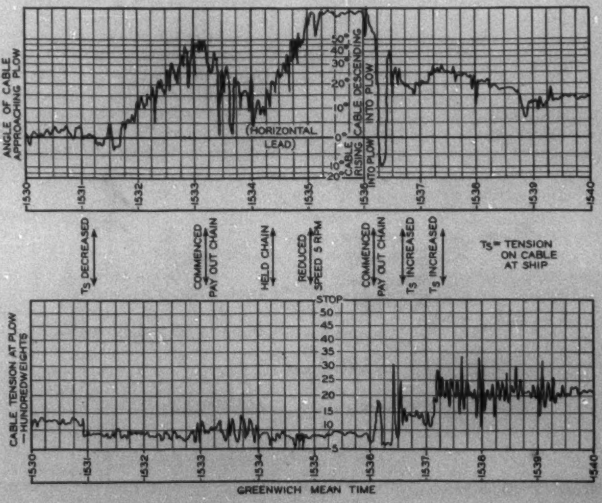
It is impossible to retrace any charted route with exactness. The irregularities which are apt to cause suspension are extremely small in extent, from the navigational viewpoint. No sounding machine on a ship rising and falling to a swell could possibly detect them. Their danger lies in the rate of change of ground slope, not in the degree nor amount of slope. An advance survey of the ground with one of the pendulums, recently given the name of "clinometer," mounted upon a small sled can and does serve to indicate the general character of the bottom, but cannot be relied upon to provide any information as to individual irregularities to be encountered. The only prudent practice at present is therefore to use a type of cable of high specific gravity and with enough unit weight in water to come within the sensitive range of the ship's dynamometer, and to place that cable in the trench with the least possible residual tension.

Devices have been considered which would furnish a pull on the cable by the plow itself, thereby relieving the cable of tension behind, but their application is difficult. We are trying to perform an operation in which over a period of several hours, perhaps 150 tons or more of cable are passed uninterruptedly through a hole only $2^3/_4$ inches wide which is inaccessible and out of sight. Given a practical solution of the problem of the power supply, any hauling device is apt to go wrong at times. If for any reason the machine failed to maintain a speed as great as the speed of the plow's advance or the cable became jammed, its grip would be a liability rather than an asset. Traction from caterpillar treads could be used as a source of power but slippage would be a serious problem. There are already three lines between the ship and plow. Addition of a power transmission line to an electric motor on the plow would call for prodigious feats of seamanship if it were to be handled successfully in the open ocean. As it is, operations are confined to the very best of weather and this cannot be counted upon to last long off the Irish coast nor to give much warning when it passes.

Adjusting Length of Towline

It will be observed that in adjusting towline length, there are two conditions to be met: The control of the vertical component of towing tension at the plow and the need for keeping the plow back of the critical point where the cable is landing. In hard ground, more prevalent out to 250 fathoms depth than beyond, it is necessary even with the heavy all-chain towline to keep the plow far behind the landing point of the cable,

Figure 15. Behavior of cable as plow passes through critical point (from 1HR record)



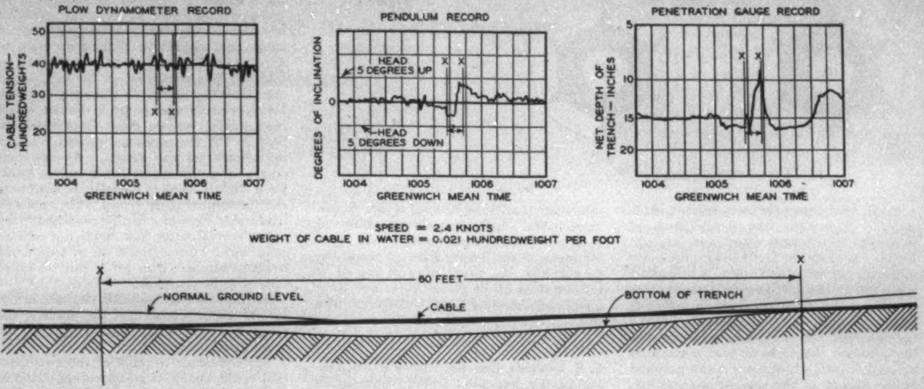


Figure 16. Indication of possible cable suspension, from instrument records

whereas in very soft ground farther out it may be necessary to pay out the entire towline to put the plow far enough astern to keep clear of the critical point. It is hoped that by continuation of model experiments a form of share developing less resistance can be evolved, which will improve the first condition. The second can always be met by having plenty of reserve towline in the locker.

Core Soundings

In determining the consistency of the bottom, a streamlined weight carrying fins set at a slight angle to give it rotation like a rifle shell is allowed to drop to the bottom on a special stranded sounding wire with ball-bearing swivel attachment. Fixed to the lower end of the weight is a bit made of three-quarter inch pipe which is forced into the ground by the impact and brings up a core of bottom material. From the appearance of the material and depth of penetration of the bit, a rough idea can be obtained of the probable towing resistance. This useful device was developed by the commanding officer of Western Union's cable ship "Lord Kelvin," Captain M. H. Bloomer, whose enthusiasm and pioneering skill, both as a navigator and seaman, have been invaluable to the whole plowing development.

Table I. Summary of Data From Plow Instruments

	4PZ	1HR
Cable tension at plow (hundredweights)		
Maximum	45	31
Minimum	11	9
Average	30	19
Vertical angle of cable into plow (degrees)		
Maximum	+50	+30
Minimum	− 5	−10
Average	+10	− 1.3
(+ = downward into plow)		
Ground slope (degrees)		
Maximum	4	5
Net depth of trench (inches)		
Maximum	over 20	over 20
Minimum	7	3*
Average	14	9

* Momentary only.

Cables Trenched

During the past summer (1938) Western Union's *4PZ*, the high-speed loaded cable, and *1HR*, the direct Paris cable, have been trenched across number 7 trawling ground and although only time can furnish conclusive proof of the success attained, the instrument records look good. At no point along either route (*4PZ*, $24^1/_2$ nautical miles; *1HR* 18 nautical miles) did the share come completely out of the ground. Table I gives a summary of the technical data obtained from the plow instruments. Only one really bad spot was recorded from the point of view of suspension across an irregularity on either route. This is the example given in figure 16. Although crossings were made in the vicinity with the depthometer it could not be found, but this is not surprising considering its small extent. Ground resistance eased off on the *4PZ* route beyond 250 fathoms but the *1HR* was hard going all the way out to 400 fathoms where the plowing terminated.

There were parts toward the western end of both jobs where the cable lead was not good because with the length of towline available the plow could not be brought far enough astern to avoid the critical point. Cable tensions carried in the eastern part of *4PZ* were much higher than on *1HR*, whereas the penetration on *4PZ* was more satisfactory at the western end. Due to continued hard ground in the deeper parts of *1HR* the vertical component of towing tension at the plow even with full towline rose until it appears that the share was prevented from maintaining its full grip.

The outlook is for better results with more practice in deep water and increased length of chain towline. The plow is still in its infancy. Eventually it is hoped to handle lighter types of cable and to develop auxiliary uses such as the protection of harbor cables from ships' anchors, and the burying of military cables.

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3. United States Patent Number 2,067,717.

4. Determining Anchor Holding Power From Model Tests, Lieutenants Leahy and Farrin. The Society of Naval Architects and Marine Engineers Transactions, volume 43, 1935, pages 105–14.

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8. United States Patent Number 2,142,136.

10. United States Patent Number 2,131,445.

Discussion

W. S. Gorton (Bell Telephone Laboratories, Inc., New York, N. Y.): To one who has been familiar with the unpredictable and the unknown factors involved in the laying and picking up of submarine cables, Mr. Lawton's paper presents a striking record of engineering achievement. It is significant,

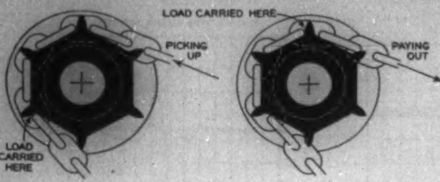

Figure 1

I think, that this advance has been made possible largely by the development of measuring instruments which have brought within the realm of the known previously unknown factors, and that it therefore conforms to the well-known criterion that we can make little progress in scientific knowledge until we can measure the quantities involved. It is most appropriate that this criterion should have been enunciated by Lord Kelvin, whose name is so prominent in the history of the submarine-cable art. All the resources of engineering, however, would have been of no avail without the ability instantly to adapt the various controls to meet the exigencies of sea and weather. This required seamanship of a high order.

The thoroughness of the treatment does not leave much room for questions, but I should like to ask Mr. Lawton why the hydraulic bellows system, used to measure the pull of the chain, had trouble from air leakage. Systems of this sort are widely used, and the makers seem to have overcome the leakage problem. It would seem that a spring could be used to exercise a force on the bellows and prevent the pressure from ever falling below atmospheric. I should be glad to have a fuller explanation of the action of the wildcat; it is not clear to me why the chain has to be made to such rigid specifications for pitch uniformity.

J. J. Gilbert (Bell Telephone Laboratories, Inc., New York, N. Y.): The procedure of plowing in submarine cables which has been described is a valuable contribution to the submarine-cable art. The solutions to the rather difficult mechanical problems in the design of the plow are very ingenious and the operations involved in its use represent a great advance in cable-laying technique. It is hoped that the expectations of the author will be fully realized, so that plowing will prove to be an unfailing means of placing cables where they will not be interfered with by other users of the ocean bottom. The paper mentions precautions that have been taken toward keeping the plow right-side up on the ocean bottom. I would be interested to know whether in actual experience the plow upsets very often. Also, is there any danger when the plow upsets of its righting itself in the wrong direction, that is, of turning a side somersault? The paper gives a very interesting summary of cable interruptions in the trawling areas off the British Isles. I would like to ask how the situation with regard to interruptions in the Nova Scotia and Newfoundland trawling areas compares with this.

C. S. Lawton: One difficulty with air leakage in the hydraulic bellows lines arises from the fact that the gauges on the forecastle head must be removed for safety in bad weather. This means having a cock and union coupling just under each gauge, the tightness of which is not easily maintained. Also, an hour may elapse between the time when the dynamometer is put in readiness for operation and the time when the plow is landed on bottom and towing tension builds up. During lowering a check must be kept on the chain tension in order to keep a proper adjustment of the load between towline and lowering line, but the chain tension does not rise high enough during this period to overcome all the vacuum on the dynamometer gauges.

A spring, such as Doctor Gorton suggested, could be employed to keep the lines above atmospheric pressure while the dynamometer was not in use, but if left in place during operation it would interfere with the readings. We are in fact using an equivalent arrangement now, but it is only partially effective for that reason.

In regard to chain uniformity, figure 1 of this discussion illustrates the preferred designs where space allows two wildcats to be fitted: one for picking up and the other for paying out with the pitch of the pockets set as explained in the text of the paper. In paying out chain under load, if the pitch of the pockets and consequently the snugs be slightly less than that of the chain, the oncoming link has more clearance in getting over the snug (at the bottom of the sketch) and a slight irregularity of chain pitch will not matter if this normal clearance is enough. As each snug comes off at the top, the whole chain moves forward slightly so as to bring the load onto the preceding snug. This little readjustment does no harm but is necessary to take care of irregularities in pitch. However, if this same cat is used for picking up, riding and jumping is bound to occur, as the conditions are reversed. In order to function smoothly on chain containing pitch irregularities the snugs and pockets for picking up must be slightly greater in pitch than the chain, so that the load is carried on the snug where the chain is coming off, the chain actually being pried off the cat by a circular wedge held against the deep groove into which the links in the vertical plane project. This is not shown on the sketch. As the snug comes free, the whole chain moves backward slightly so as to transfer the load onto the preceding snug. By this means a reasonable clearance can be maintained between the oncoming link at the top and the snug which rises to meet it, so that small irregularities in chain pitch can be taken care of without trouble.

As there was no space for two cats in our case it was essential that the pitch of the snugs and pockets be exactly right for the chain at all points.

The difference in pitch of the two wildcats in the figures is greatly exaggerated of course.

With reference to Mr. Gilbert's discussion, in the early designs of plows in which the weight was much less than the present design, hoops were fitted over the top of sufficient strength to support the full weight if the plow landed upside down, and of such a shape as to cause it to roll over immediately.

This is not necessary now that we are using instruments which give instantaneous indications on board ship of the plow's behavior. The pendulum will not assume the position of 0 degrees (plow deck horizontal) or anything approaching this unless the plow is right-side up. If the plow were to capsize, the pendulum would swing over against one of its two stops and remain there, giving a reading greater than 90 degrees.

Since the instruments have been installed there has never been a case where the plow has turned over. The attachment of the lowering line is made well above the plow's center of gravity and the only critical moment is after release of this line when the towline is still snubbed up short to keep it from fouling and the ship's head is rising and falling to the swell. Once the towline has been paid away to a length substantially greater than the depth of water there is no danger on any ordinary bottom. Trial tows made with a transverse pendulum in use over long distances have shown no dangerous canting of the plow to either side.

Trawling off Nova Scotia and Newfoundland appears to be on the increase but to date it does not cause as much trouble as it does off Ireland. The cables affected on the European side are mostly main transatlantic sections, whereas on this side the damage is mostly confined to short connecting cables of lesser individual importance from the traffic standpoint. It is expected to use the plow on this side after the other side has been protected.

Current Distribution in a Rectangular Conductor

JOHN L. DALEY
ASSOCIATE AIEE

Synopsis: The extensive use of rectangular conductors for large alternating currents has made the determination of their electrical characteristics a problem of practical importance. Although these conductors are usually used in groups and in special configurations, no solution other than that of direct measurement has been given even for the basic problem of the distribution of current in a single isolated conductor. The mechanical complications of the direct measurement method are great, and the results obtained are necessarily an approximation.

This paper presents a method by which the current density inside a rectangular section may be analytically determined if the surface current density, a comparatively easy quantity to determine, is known.

THE distribution of current over the cross section of a conductor is the determining factor in the calculation of voltage drop, power loss, and mechanical forces. When uniform, as in direct current, the calculations are comparatively simple. A conductor carrying an alternating current, however, has a varying magnetic field associated with it which causes a variation in current density, both in magnitude and phase at each point of the cross section. This gives rise to great difficulty in the calculations.

The magnetic field inside the conductor, which is the cause of the nonuniform distribution, is produced by the current in the conductor, and currents in adjacent conductors. In view of this, early analytical investigations were limited to single isolated conductors of a circular cross section. Here, radial symmetry makes a one-dimensional analysis possible, Heaviside[1] and Lord Kelvin[2] obtained the solution in terms of Bessel functions.

If the conductor is not circular, or if more than one conductor is considered, the problem is two dimensional, and greater difficulty is experienced. Special cases of two circular conductors have been solved.[3–5] Dwight[6] has given the results for tubular and flat conductors.

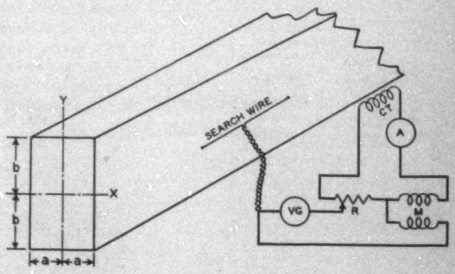

Figure 1. Cross section of rectangular conductor, showing co-ordinate system and measuring circuit

Various attempts have been made to approximate the current distribution in rectangular conductors. These have been completely experimental, in that the current distribution was measured directly,[7] or calculated by assuming the conductor to be made up of a number of small sections over which the current density was assumed constant.[8] Others[9,10] have considered elliptical cross sections.

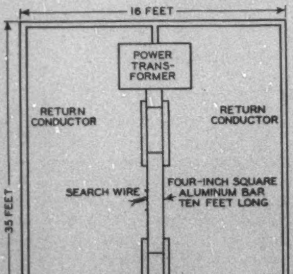

Figure 2. Diagram of connections for test

Object

This paper presents a method of determining the current distribution over a rectangular section. It is partly experimental and partly analytical, in that the boundary conditions for the differential equation of current distribution are measured on the surface of the conductor, and by calculation, the current density at any point inside the conductor determined. A single isolated bar is considered in this initial work, but with little change, the general case may be solved.

Theory

The conductor is assumed to be of unit permeability, homogenous in composition, sufficiently long and far enough removed from its return circuit to be unaffected by it. With these conditions, end effect and proximity effect are absent and the current distribution over the cross section may be considered two dimensional and all flow axial.

The origin of co-ordinates (x,y) is at the center of the rectangle whose dimensions are $2a$ and $2b$ (figure 1). Mathematical derivations are given in appendix I, and are briefly as follows:

1. From Maxwell's equations, the differential equation of the current density is obtained.

2. The solution of the differential equation is obtained, using the measured values of the surface current density as boundary conditions. The process is the conventional method of product solutions and sums of these.[11]

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This paper is part of a dissertation presented for the degree of doctor of philosophy at Yale University.

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[1] For all numbered references, see list at end of paper.

3. The current density is given by

$$U_{x,y} = U_{a,b}\frac{\cosh \epsilon x \cosh \alpha y}{\cosh \epsilon a \cosh \alpha b} + \Sigma A_n(\cosh \mu_n x \cos n y) + B_m(\cosh \Psi_m y \cos m x) \quad (1)$$

where

$U_{x,y}$ = current density at the point (x, y)
$U_{a,b}$ = current density at the point (a, b), a corner of the cross section
$\epsilon, \alpha, \mu_n, \Psi_m$ = constants defined in appendix I
A_n, B_m = coefficients of the Fourier series developed from the measured values of surface current density
x,y = co-ordinate distances measured in centimeters

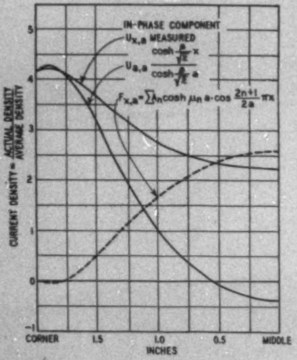

Figure 3. In-phase component

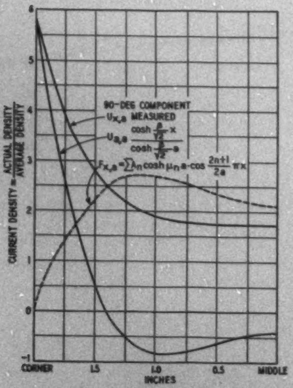

Figure 4. Ninety-degree component

Figures 3 and 4. Measured values of current density and boundary conditions

Four-inch-square aluminum bar at 60 cycles, 29 degrees centigrade

4. The a-c resistance of the conductor may be calculated easily and directly from the real part of the term (see appendix II)

$$Z = \frac{\rho U_{a,b}}{\int U_{x,y}\,dx\,dy} \text{ ohms per unit length}$$

Application to a Square Bar

As a check on the theory presented, a four-inch-square aluminum bar was tested. The circuit dimensions are shown on figure 2. The surface current density was measured as described in appendix III. For convenience, the values are given in terms of (actual current density)/(average current density) so that an ordinate of, say, 2.5, means that the current density at that point is 2.5 times as great as it would be if the current distribution were uniform (figures 3 and 4).

The square bar allows simplifications in both test procedure and calculation. Since the bar dimensions are equal and the current distribution symmetrical about the origin, equation 1 takes the form

$$U_{x,y} = U_{a,a}\frac{(\cosh \beta x/\sqrt{2})(\cosh \beta y/\sqrt{2})}{\cosh^2 \beta a/\sqrt{2}} + \Sigma A_n\left(\cosh \mu_n x \cos\frac{2n+1}{2a}\pi y + \cosh \mu_n y \cos\frac{2n+1}{2a}\pi x\right)$$

The function, $F_{x,a}$, which is expanded in a Fourier series, is equal to the difference between the measured surface current density, $U_{x,a}$, and the calculated quantity, $U_{a,a}(\cosh \beta x/\sqrt{2})/(\cosh \beta a/\sqrt{2})$. This function vanishes at the end points, thus the series in odd half harmonics is convergent at these points.

$$F_{x,a} = U_{x,a} - U_{a,a}\frac{\cosh \beta x/\sqrt{2}}{\cosh \beta a/\sqrt{2}}$$

$$= \Sigma A_n \cosh \mu_n a \cos\frac{2n+1}{2a}\pi x$$

$$n = 0, 1, 2, 3 \ldots$$

is shown on figures 3 and 4.

By application of the usual rules,[13] the coefficients A_n were determined. For the four-inch-square aluminum bar operating at 29 degrees centigrade, the constants are (using $\rho = 2.84 \times 10^{-6}$ ohms per centimeter cube, $a = 5.092$ centimeters, $f = 60$ cycles):

n	μ_n	$A_n(\cosh \mu_n a)$	$\cosh \mu_n a$
0	$0.94+j0.90$	$2.46+j3.08$	$11.46-j\,58.71$
1	$1.17+j0.71$	$0.29-j1.00$	$-169.23-j\,90.83$
2	$1.63+j0.51$	$-0.18+j0.17$	$-1705\quad +j990$
3	$2.19+j0.38$	$0.06-j0.03$	$-12{,}570+j32{,}800$

$U_{a,a} = 4.14 + j5.90,\ \beta = 0.9133\,(1 + j)$

The contour charts, figures 5 and 6 show values of current density and phase angle at each point of the cross section as determined by calculation. A three-dimensional sketch of lines of equal current density is given in figure 7.

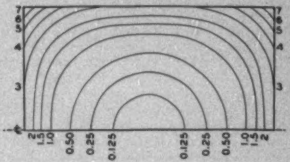

Figure 5. Lines of equal current density

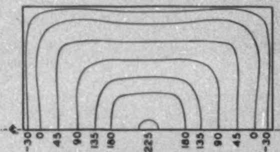

Figure 6. Phase variation in degrees from phase of total current

(– indicates lead)

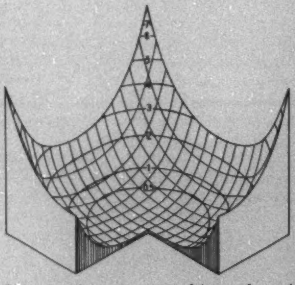

Figure 7. Isometric view of lines of equal current density

Figures 5–7. Distribution and phase variation of current density

Four-inch-square aluminum bar at 60 cycles, 29 degrees centigrade

The a-c resistance of the bar per unit length is the real part of

$$Z = \frac{\rho U_{a,a}}{\int U_{x,y}\,dx\,dy} = \frac{4.14 + j\,5.90}{103.71} \times 2.84 \times 10^{-6}$$

or 11.76×10^{-8} ohms, which is slightly more than four times the d-c resistance.

Verification of Solution

The validity of the expression for current distribution was established by comparing: (1) its integrated value with the known total current in the bar, and (2) the individual values at particular points with those obtained by direct measurement.

1. Comparison of Calculated Total Current With Measured Value

$$\underset{\substack{\text{Cross}\\\text{section}}}{\int\int} U_{x.y}dx\,dy =$$

$$\int\int\left\{U_{aa}\frac{\left(\cosh\frac{\beta x}{\sqrt{2}}\right)\left(\cosh\frac{\beta y}{\sqrt{2}}\right)}{\cosh^2\frac{\beta a}{\sqrt{2}}}+\right.$$

$$\Sigma\frac{A_n}{\cosh\mu_n a}\left[\cosh\mu_n x\cos\frac{2n+1}{2a}\pi y+\right.$$

$$\left.\left.\cosh\mu_n y\cos\frac{2n+1}{2a}\pi x\right]\right\}dx\,dy$$

$$=\int_{-a}^{+a}\int_{-a}^{+a}U_{x.y}dx\,dy=4\int_0^a\int_0^a U_{x.y}\,dx\,dy$$

$$=U_{a.a}\frac{8}{\beta^2}\tanh^2\frac{\beta a}{\sqrt{2}}+\Sigma(-1)^n\times$$

$$\frac{A_n 16a}{(2n+1)\pi\mu_n}\tanh\mu_n a$$

$n = 0, 1, 2, 3\ \ldots$

$\beta^2 = j\,1.668$
$\tanh^2\beta a/\sqrt{2} = 0.9947 - j\,0.0005$
$\tanh\mu_0 a = 1.0003 + j\,0.0004$
$\tanh\mu_n a \approx 1.0000 + j\,0.0000$
$n = 1, 2, 3$

The following tables show the values of each integral term, and the effect on the sum of including the next term. Value of each term:

$$\frac{8}{\beta^2}U_{a.a}\tanh^2\frac{\beta a}{\sqrt{2}} = 27.91\quad - j\,19.59$$

$$+\frac{16aA_0}{\pi\mu_0}\tanh\mu_0 a = 77.55\quad + j\,10.39$$

$$-\frac{16aA_1\tanh\mu_1 a}{3\pi\mu_1} = 1.74\quad + j\,6.32$$

$$+\frac{16aA_2\tanh\mu_2 a}{5\mu_2\pi} = -0.35 + j\,0.66$$

$$-\frac{16aA_3\tanh\mu_3 a}{7\mu_3\pi} = -0.09 + j\,0.07$$

Value of integral:

Including $n = 0$ term $105.46 - j\,9.20$
$n = 1$ term $107.20 - j\,2.88$
$n = 2$ term $106.85 - j\,2.22$
$n = 3$ term $106.76 - j\,2.15$

The actual value, on the basis of an exactly square section, since the reference quantity used was average density, is equal numerically to the area of the bar $103.71 + j\,0$. The agreement is thus approximately three per cent.

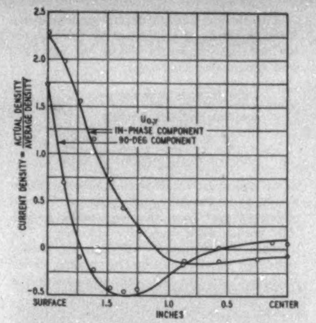

Figure 8. Comparison of calculated and measured values

Measured points indicated by dots

$U_{o,y}$ is the current density at points on Y axis, figure 1

2. Comparison of Calculated and Measured Values

By using two two-by-four-inch bars clamped rigidly together to give the square section for test, it was possible to insert measuring wires to determine the values of the current density along a plane through the center of the bar. This comparison is shown on figure 8.

Conclusions

1. A method for determining the current density at every point of the cross section of a rectangular conductor of any dimensions has been developed.
2. The method is partly experimental and partly analytical, in that the solution of the differential equation of the current density is obtained using the measured boundary values.
3. A-c resistance of the bar is determined.
4. Application of the method to a square bar is given, and curves showing the magnitude and phase of the current density over the cross section presented.
5. An extensive investigation on bars of various dimensions is now in progress. It is hoped that the necessary conditions for a completely analytical solution will be determined.

Appendix I. Mathematical Derivations

Maxwell's equations in centimeter-gram-second practical units are

$$\nabla XH = 0.4\pi U \tag{2}$$

$$\nabla XE = -10^{-8}\frac{\partial B}{\partial t} \tag{3}$$

where H is the magnetic field, E the dielectric field, U the current density, and B the flux density. Since the only component of current density is in the Z direction, and the permeability unity (2) and (3) may be written as

$$\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}=0.4\pi U$$

$$\frac{\partial E}{\partial x}=\rho\frac{\partial U}{\partial x}=\frac{\partial H_y}{\partial t}10^{-8}$$

$$\frac{\partial E}{\partial y}=\rho\frac{\partial U}{\partial y}=\frac{\partial H_x}{\partial t}10^{-8}$$

Combining these, the well-known differential equation of current distribution is obtained

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}=\frac{4\pi j\omega U10^{-9}}{\rho}=\beta^2 U \tag{4}$$

Solutions of (4) obtained by the method referred to hereinbefore[11] may be expressed in the form

$\cosh\epsilon x\cosh\alpha y$
$\cosh\mu x\cos ny$
$\cosh\Psi y\cos mx$

where

$\epsilon^2 + \alpha^2 = \beta^2$
$\mu^2 - n^2 = \beta^2$
$\Psi^2 - m^2 = \beta^2$

If the sum

$$U_{x.y} = C\cosh\epsilon x\cosh\alpha y + \Sigma A_n\cosh\mu_n x\cos ny + \Sigma B_m\cosh\Psi_m y\cos mx$$

is assumed as a solution, and

$$C=\frac{U_{a.b}}{\cosh\epsilon a\cosh ab}$$

$$n=\frac{2r+1}{2b}\pi$$

$$r, s = 0, 1, 2, 3, \ldots$$

$$m=\frac{2s+1}{2a}\pi$$

the coefficients A_n and B_m may be determined by application of the usual rules for Fourier coefficients.[12]

$$A_n=\frac{1}{b\cosh\mu_n a}\int_{-b}^{+b}\times\left[U_{a.y}-U_{a.b}\frac{\cosh\alpha y}{\cosh\alpha b}\right]\cos ny\,dy$$

$$B_m=\frac{1}{a\cosh\Psi_m b}\int_{-a}^{+a}\times\left[U_{x.b}-U_{a.b}\frac{\cosh\epsilon x}{\cosh\epsilon a}\right]\cos mx\,dx$$

The series thus obtained reduces to the boundary values at the surface, and is convergent in the interval $(\pm a, \pm b)$.

Appendix II. Resistance at 60 Cycles

1. A-c resistance may be calculated from the ratio of power loss to current squared:

$$R_{a-c} = \frac{\int_y U_{x,y}^2\, dx\, dy}{[\int U_{x,y} dx\, dy]^2} \text{ ohms per unit length}$$

2. A simpler and more direct calculation gives the same result. Since all flow is axial, the potential difference between points in any two planes perpendicular to the axis of the conductor is the same.

At the corner of the bar, the magnetic flux linking this filament is wholly external to the conductor. Thus the drop produced by the current and resistance in this filament is the potential difference between the two planes, if only the flux inside the conductor be considered.

The term internal impedance may be defined as that due to the resistance of the isolated conductor, and the inductance due to the flux linkages inside the conductor.

$$Z = \frac{\rho U_{a,b}}{\int U_{x,y} dx\, dy} \text{ ohms per unit length}$$

The real part of this expression is the a-c resistance per unit length.

Appendix III. Method of Measurement

The current density at any point of the conductor may be measured by means of an insulated wire laid along the bar, parallel to the axis and making electrical contact at each end only (figure 1). This wire is broken at the middle and the two ends brought out. The potential difference between these ends is equal to the resistance drop in the element of the bar immediately adjacent to the wire, since the induced voltage in the search wire and bar element cancel.

The measuring circuit is an a-c potentiometer. When the vibration galvanometer, *VG*, indicates a condition of balance, the voltage of the search wire is equal to the voltage produced by the current from the current transformer, *CT*, through the resistance, *R*, and the mutual inductance, *M*. Thus

$$V_{\substack{\text{search}\\\text{wire}}} = I_{\text{amm.}}(R + j\omega M) = (ir)_{\substack{\text{bar}\\\text{element}}} = U\rho l$$

or

current density in

$$\text{bar element} = I_{\text{amm.}}\left(\frac{R + j\omega M}{\rho l}\right)$$

The magnitude and phase of the current density is thus determined.

In order to have a more useful reference quantity, the particular value of current used for test was eliminated by introducing the term average density. This is defined as:

$$\text{Average current density} = \frac{\text{total bar current}}{\text{area of bar}} = \frac{I_{\text{amm.}} \times \text{current-transformer ratio}}{\text{area of bar}}$$

The current density in the bar was calculated in terms of this quantity. Thus, the surface measurements shown on figures 3 and 4 were obtained from:

$$U = \frac{\text{actual current density}}{\text{average current density}} = \frac{(R + j\omega M)\ (\text{area of bar})}{(\rho l)\ (\text{current-transformer ratio})}$$

In order to avoid errors due to stray fluxes, the measuring apparatus was located about 50 feet from the bars being tested. All leads were carefully twisted. The absence of extraneous voltages was easily tested by short-circuiting the "search wires" (figure 1) at the bus bars and using the measuring circuit in the usual manner.

This method of measurement is applicable to all current-density measurements where the variation is in one plane only, and remains constant perpendicular to this plane.[7,7a]

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Discussion

Ernst Weber (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): The method of combining the analytical solution with an experimental determination of the boundary conditions is most interesting in itself but has the disadvantage of any experimental method, namely to be applicable only to the special case under investigation. A general analytical solution would be of advantage, but could be secured only with great difficulties. Thus one could transform the rectangular boundary into a circular one by conformal mapping of the geometry. The differential equation (4) in the author's paper would, of course, then become much more complex but the boundary conditions, which now represent the major obstacle to a complete solution, could easily be satisfied.

There is, however, an approximate method available. Though the author does not give the expression for the magnetic field, one could easily obtain it from Maxwell's field equations. Constructing the magnetic field lines, one would find nearly elliptical curves, which partly penetrate into the conductor and partly close through the surrounding air. By a slight deformation of these magnetic field lines, namely making one of them exactly coincide with the rectangular boundary of the conductor, one would have the boundary conditions $H_x = 0$ at $x = \pm a$ and $H_y = 0$ at $y = \pm b$, which can be satisfied in a manner very much similar to the author's method using Fourier series expressions. Thus one would get

$$A_n = \frac{1}{\mu_n \sinh \mu_n a} \times \int_{-b}^{+b} \left[\sum_m m B_m \sin ma \cdot \cosh \psi_m y - C\epsilon \sinh \epsilon a \cdot \cosh \alpha y\right] \cos ny \cdot dy$$

and

$$B_m = \frac{1}{\psi_m \sinh \psi_m b} \times \int_{-a}^{+a} \left[\sum_n n A_n \sin nb \cdot \cosh \mu_n \Psi - C \cdot \alpha \sinh \alpha b \cosh \epsilon x\right] \cos mx \cdot \alpha x$$

corresponding closely to the author's expressions and one would have to add the additional condition

$$\int\int U\, \alpha x\, dy = I$$

which will determine the constant C. This permits direct evaluation of the current distribution and should not deviate very much from the measured one. It would be interesting to compare the results in both cases and possibly use this approximation for precalculation of field and current distributions as well as for a determination of the resistance increase at alternating applied voltages.

In the method of the author it is, of course, not necessary to verify the solution by computing the total current numerically. This can serve only to demonstrate the relative importance of the various terms in the infinite series in the particular case chosen.

John L. Daley: Doctor Weber's comment on the limitations of any experimental method is appropriate. However, the method described in the paper is not limited to the particular application used therein for illustration. The method is quite general, but in each case an experimental de-

The Submarine-Cable Depthometer

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THE PROBLEM of plowing submarine cables[1] into the ground or sand making up the bottom of the ocean requires a means of checking the depth of burial of the cable after the plowing operation has been completed. Measuring the actual depth in inches below the surface of the ground is the purpose of a magnetic detecting and measuring device known as the cable depthometer. This magnetic detector is contained in a sled as shown in figure 1, designed for towing by the cable ship along the ocean bottom. The detecting operation utilizes the fact that ocean cables have a protective sheath of iron or steel wires around the copper core and the insulation. The magnetic field arising from the magnetization of the cable sheath, together with the distortion created in the earth's magnetic field by the cable sheath, generates an electromotive force in detecting coils in the sled, when these coils are moved in a substantially horizontal plane through such a field.

Figure 1. Cable depthometer sled

As the electromotive force generated in a single detecting coil or set of coils is a function not only of the speed at which the coils pass over the cable, but also of the amount and distribution of iron or steel in the cable sheath, of the degree of magnetization, of the strength and direction of the earth's field, of the gain or amplification of the amplifying and recording apparatus used to measure the signal on board the cable ship, and of other factors, determination of the distance between the sled and the cable, based upon the signal strength only, requires the evaluation of too many factors. To make compensation unnecessary for speed and other factors, a second set of detecting coils is mounted in the sled six feet behind the first set, as shown in figure 2.

Figure 2. Sled framework showing forward and after coil pots

The first coil set is mounted in a protecting pot at the forward end of the sled, and the second coil set in a similar pot at the after end. The second set of coils, known as the "after" set, is so constructed that its voltage-response versus distance-to-cable characteristic differs considerably from that of the first or "forward" set of coils. As the sled is towed over the cable, signals are delivered in sequence from first the forward and then the after set of coils. Measurement of the distance to the cable is accomplished by observing the ratio of the signal from the forward set to that from the after set, this ratio being a function of the distance only between the sled and the buried cable, increasing from 1.25 at zero inches of depth to 4.4 at 15 inches. Doubling the speed of the sled and the attached detecting coil sets will double the signal from both sets of coils, without changing the ratio.

This sequence of signals is transmitted to the amplifying and recording apparatus on board the cable ship through a pair of wires in the center of the sled towing line. As the frequency of such signals is in the neighborhood of one cycle per second, and as the maximum signal amplitude obtainable from the type of cable used in the plowing is approximately 0.3×10^{-6} amperes at 15×10^{-6} volts, a d-c amplifier of special design is used. The input circuit consists of cam-operated breaker points which provide sharp interruptions of the input current through the low-voltage winding of a transformer, inducing relatively high-voltage peaks in the high-voltage winding. By this method, the approximately one-cycle-per-second signal generated in the detecting coils becomes the modulation on a 240-cycles-per-second signal, for amplification with a conventional transformer-coupled amplifier tuned to 240 cycles per second. The output of the amplifier is rectified and operates a d-c recorder, making an inked record of the signals. It is by inspection of this inked record that the ratio of the forward to the after signal can be computed and the depth of the buried cable at the point of crossing quickly determined.

As the generation of signals in the detecting coils depends upon motion of the coil sets through the magnetic field sur-

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[1] For all numbered references, see list at end of paper.

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termination of the boundary conditions is necessary.

The approximate method suggested has its advantages. In fact, with appropriate adjustments, the method used by Bewley and Poritsky ("Intersheet Eddy Current Loss in Laminated Cores," ELECTRICAL ENGINEERING, March 1937, pages 344–5), on a related problem, would give a similar treatment.

The accuracy of any approximate method could be established by comparison of a particular case with the exact method presented in my paper.

The use of conformal mapping presents an interesting possibility.

The second verification of the solution was given in the paper to demonstrate the convergence of the series. In the case of least rapid convergence, that of the square cross section, reasonable accuracy is obtained with only a few terms.

rounding the cable, the maximum signal results when the sled follows a course perpendicular to the line of the cable. The procedure followed in the operation of the sled is to tow it back and forth across the buried cable, charted as shown in figure 3, obtaining a number of crossings in each mile. While such a series of readings is far from being a continuous record, nevertheless it affords an opportunity for judging the performance of the cable plow.

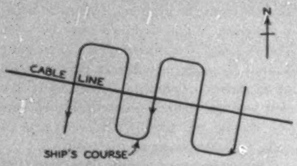

Figure 3. Towing course of ship

Amplifying the statement in the opening paragraph, the signal indicating the presence of a magnetic object such as an ocean cable, is the result of the progression of detecting coils from the uniform magnetic field of the earth into the nonuniform magnetic field surrounding the magnetic object, and thence back into the uniform field of the earth, the signal intensity being proportional to the rate at which the flux changes through the detecting coils. In the case of a long object such as an ocean cable, the field is the result of three factors. First, magnetic poles are formed longitudinally along the cable sheath, with lines of force substantially parallel to the cable between poles, much on the order of a long bar magnet. This type of magnetization produces very little flux linkage with the detecting coils. Second, magnetic poles are formed in planes perpendicular to the length of the cable; thus one side of the cable sheath becomes a north pole and the opposite side a south pole. This type of magnetization, which may be called "transverse magnetization," results in considerable flux linkage with a detecting coil, as shown in figure 4. Third, the high magnetic permeability of the cable sheath causes a distortion in the earth's magnetic field. Motion of the detecting coil or coils into this region induces a voltage in one direction in the circuit as the flux linkage is increased and voltage in the opposite direction as the flux linkage decreases.

Since some types of motion of a single detecting coil in the earth's field generate very large interfering voltages, it is necessary to add a second coil, having the same product of turns times average area as the first coil, and parallel to it. The two coils are then connected in series differentially, that is, poled oppositely, with the result that voltages in the coils induced by rotary motion in the earth's field are 180 degrees out of phase in the circuit and cancel. Two coils, one above the other, rigidly fastened together and differentially connected, are shown in figure 5 as they progress in the horizontal arrow direction over the cable shown in cross-section, with the iron sheathing wires *a*, the gutta percha insulation *b*, and the copper core *c*. For the sake of simplicity, only the lines of force due to the transverse magnetization of the cable are shown with the polarization assumed horizontal, omitting the lines of force of the earth's field. Since the detecting coils are differentially connected, some degree of cancellation of the signal from the cable is experienced. However, since the upper coil is at a greater distance from the cable than is the lower coil, a comparatively low voltage is generated and cancellation of the voltage generated in the lower coil is small. The greater the distance between the coils, the less the cancellation. However, the physical considerations of keeping the coils parallel and preventing relative motion between them, make the smaller values of separation desirable.

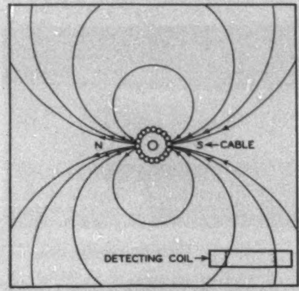

Figure 4. Transverse magnetization of cable showing flux linkage with one coil

If the mere detection of the presence of a magnetic object such as an ocean cable is all that is required, the use of one pair of detecting coils is sufficient, as the exact voltage magnitude will then be of little importance. In the determination of the depth to which the cable is buried, the use of the second set of detecting coils makes proper compensation for speed and other factors. The difference in characteristics between the second or after coil set and the first or forward set is illustrated in figure 6. The ordinates are percentages of the signal at zero inches depth, and the abscissas distances between the bottom of the coil pots and the cable, both being logarithmic scales. It is to be noted that the ratio of the forward signal, designated by curve *F*, to the after signal, curve *A*, is unity at zero inches, while at 15 inches the *F* ordinate is 3.5 times that of the *A* ordinate. In actual practice, however, the coil sets are so constructed that the ratio of *F* to *A* at zero inches is 1.25, increasing to 4.4 at 15 inches. The relationship between the ratio of the two signals and the distance between the bottom of the sled and the cable is shown in figure 7.

Actual records are shown in figure 8, the right-hand record being that of a one-inch burial of the cable and the left hand record that of an eight-inch burial. In general, there are two distinct voltage peaks in the signal from each coil set, one peak when the flux is increasing most rapidly through the coils and one when the flux is decreasing most rapidly. These are observable in the left-hand record of figure 8 and are designated *a* and *b* for the forward coil set which passes the cable first, followed by the two peaks *c* and *d* for the after coil set which is spaced six feet behind the forward set. Whether the two peaks of each signal are equal in magnitude or not depends upon the position of the composite magnetic vector representing the field around the cable sheath plus the distortional effect of the iron in the sheath on the earth's field. If this vector is perpendicular to the line of motion of the detecting coils in the sled, the two peaks will be equal in magnitude. Calculation of the ratio is based on the average.

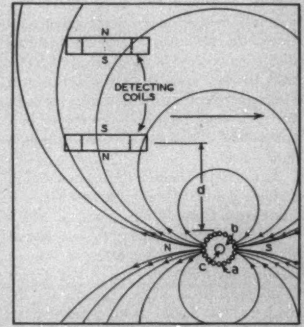

Figure 5. Transverse magnetization of cable showing flux linkage with balanced coils

There are numerous practical problems to be solved in developing a mobile magnetic detector operating on the nonuniform magnetic field around iron or steel objects. The choice of design is restricted by the necessity for dragging such a detector along a rough ocean bottom, under water pressures up to 1,200 pounds per square inch and at distances behind the ship up to 6,000 feet.

The most serious problem is that of elimination of potentials due to some types of motion of the detecting coils through the earth's field. Coil sets must be constructed so that the magnetic vector of the lower coil is equal in magnitude and opposite in direction to the magnetic vector of the upper coil. In other words, with n coils rigidly fastened together in any one system, the vector sum of all their magnetic vectors must be zero. In a two coil system, the number of turns times the average area of one coil must equal that of the other coil, the two must be differentially connected in the circuit, and must be parallel. In detecting magnetic objects the size of an ocean cable, it was experimentally determined that the cancellation of the earth's field or what was termed a "balance" must be correct within one part in 12,000 if the interference were to be held below two per cent of full scale. As the product of the number of turns and the average area of each of the coils used is 25,380 turn inches squared, the coils must be within approximately 2 turn inches squared of each other. The winding of the coils must also take into consideration the high pressures to be encountered and the prevention of coil deformation which would change the average area of the turns.

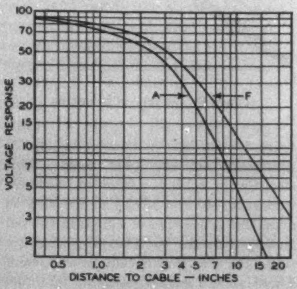

Figure 6. Voltage response-distance characteristics

The other consideration is the matter of parallelism. Two coils such as shown in figure 9 are assumed to be rigidly fastened together. They are also assumed to be out of parallel or balance by the fixed angle a. The entire system is first considered stationary in the earth's field H, with the lower coil at an angle of wt with the field and the upper coil at an angle of $wt - a$ with the field.

The following definitions are used:

W = rotative speed of the coil system in the earth's field
N_1 = number of turns in the lower coil
N_2 = number of turns in the upper coil
A_1 = average area of the lower coil
A_2 = average area of the upper coil
H = magnetic intensity of the earth's field
B = $\mu H = H\mu$ is unity as the balancing is conducted in a location free from magnetic objects
ϕ_1 = flux linkage of the earth's field with the lower coil
ϕ_2 = flux linkage of the earth's field with the upper coil

The flux linkages of the two coils can then be written:

$$\phi_1 = BN_1A_1 \sin (wt)$$

and

$$\phi_2 = BN_2A_2 \sin (wt - a)$$

As the instantaneous values of the potentials generated in the coils can be written as

$$e_1 = \frac{-d\phi_1}{dt}$$

and

$$e_2 = \frac{-d\phi_2}{dt}$$

$$e_1 = -wHN_1A_1 \cos (wt)$$

and

$$e_2 = -wHN_2A_2 \cos (wt - a)$$

From inspection it is apparent that the constant terms must be equal and that the periodic terms must also be equal, that is;

$$N_1A_1 = N_2A_2 \text{ and } a = 0$$

Assuming that the angle a is finite and that the condition of $N_1A_1 = N_2A_2$ has been satisfied, the net voltage developed by rotation in the earth's field will be as follows:

$$e_1 - e_2 = -wHN_1A_1[(\cos wt) - (\cos wt - a)]$$

As long as this angle a is finite, the interference developed will be proportional to the rotative speed w of the system. As vibration or shock will develop comparatively high values of w, the experimentally determined figure of one part in 12,000 to which the balance must be held is understandable. The maximum value the angle a may have, is the angle whose sine is 8×10^{-5}, 0.0047 of one degree of arc.

Earlier in this paper the so-called "ratio" method was described, having as its basis two different coil sets which had unlike voltage-response versus distance characteristics as shown in figure 6. This difference in characteristics may be accomplished in a number of ways; for instance, the first or forward set of coils can be constructed in the flat "pancake" manner, while the second or after set of coils can be constructed with the turns concentrated at the outer diameter of the coil; in other words, the geometries of the two coils would differ. The most satisfactory method tried, however, involved coils all of similar geometries, and depends upon their disposition for the desired effect. Figure 10 illustrates the coil arrangement of the depthometer sled, in which the two coil sets are six feet apart. At any given speed, the peak signal generated in a single detecting coil will vary as one over the square of the distance between the coil and the cable, beyond a certain minimum distance. The detecting coil does not begin to operate as a point of no dimensions, and the signal generated in the detecting coil does not obey the inverse square law, until this minimum distance of approximately $1^1/_2$ diameters of the coil has been reached. To simplify calculations in the following analysis, however, it will be assumed that the signal generated varies as one over the distance squared for the entire range. The following definitions are given:

s = speed of the sled in the direction perpendicular to the line of the cable
d = distance between the bottom of the sled and the cable in inches
k = a constant involving the permeability of the cable sheath, its cross section, the vector magnetic intensity of the earth's field, etc.
$N_1A_1 = N_2A_2 = N_3A_3 = N_5A_5 = NA$
$N_4A_4 = 2NA$
e_1 = peak signal generated in no. 1 coil, e_2 in no. 2, etc.

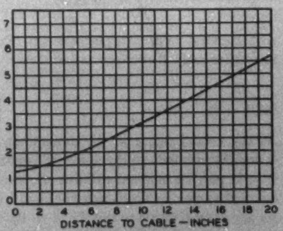

Figure 7. Ratio-distance characteristic of dephthometer

e_f = peak signal generated in the forward coil set

e_a = peak signal generated in the after coil set

The signal generated by the forward set of coils will approximate the difference between the individual coil signals, thus:

$$e_f = e_1 - e_2$$

The signal generated by the after set of coils will approximate the sum of the upper and lower coils number 3 and number 5 minus that of the center coil number 4. Note that the magnetic vectors of the upper and lower coils are in the same direction, while that of the center coil is in the opposite direction and of twice the magnitude. The vector sum of the three coils in the system is therefore zero, which fulfills the requirement that no signal be generated by rotary motion of the system in the earth's field. As the peak signal of any coil is directly proportional to the speed s, to the number of turns N, to the average area A, and to the constant k, and inversely proportional to the distance between the coil and the cable squared, the following expressions can be written:

$$e_f = e_1 - e_2 = \frac{ksNA}{(d+5)^2} - \frac{ksNA}{(d+13)^2}$$

$$e_a = e_3 - e_4 + e_5 = \frac{ksNa}{(d+5)^2} - \frac{2ksNA}{(d+9)^2} + \frac{ksNA}{(d+13)^2}$$

The ratio of the forward coil set signal to that of the after signal cancels the factors of k, s, and NA and involves only the distance d between the bottom of the sled and the cable, thus:

$$\frac{e_f}{e_a} = \frac{\dfrac{1}{(d+5)^2} - \dfrac{1}{(d+13)^2}}{\dfrac{1}{(d+5)^2} - \dfrac{2}{(d+9)^2} + \dfrac{1}{(d+13)^2}}$$

This expression can be reduced to the following:

$$\frac{e_f}{e_a} = \frac{(d+9)^2}{6(d+9)^2 - 32} = \text{the ratio}$$

As the lowest value d can have is zero, the minimum ratio is:

$$\frac{9^2}{6(9)^2 - 32} = \frac{729}{486 - 32} = 1.6057$$

As the (-32) figure in the denominator is small compared to the $6(d+9)^2$ quantity, it may be omitted without introducing much error, in which case the equation for the ratio reduces to simply $(d+9)/6$, the equation for a straight line having a slope of one in six and an intersection on the Y axis of 1.5. The following tabulation compares the calculated values with the actual experimentally determined values, also showing the calculated forward coil set signal e_f and the after signal e_a.

d in Inches	ef	ea	Ratio, Calculated Value	Ratio, Actual
0	0.03410	0.02130	1.61	1.25
5	0.00691	0.00288	2.40	2.00
10	0.00255	0.00080	3.21	3.18
15	0.00122	0.00030	4.04	4.43
20	0.00068	0.00014	4.86	5.70

The above treatment makes a number of assumptions which introduce error; however, the experimental and calculated values follow each other reasonably well.

Since the coil arrangement discussed here behaves symmetrically it is immaterial whether the sled is towed upon its top or bottom surface. The front-quarter view of the depthometer sled shown in figure 1 shows the stepped arrangement on the sides of the sled, designed to prevent riding on other than the top or bottom surfaces.

It is necessary to construct the sled and all fittings of a nonmagnetic material. Everdur, a manganese-silicon-copper alloy, is used. The completed sled is approximately ten feet in length, 21 inches high, weighs 2,600 pounds in air, and 1,800 pounds in salt water. The coil pots shown in place in figure 2 are filled with castor oil to provide a means whereby the extreme pressures at the ocean bottom can be taken care of through the relative incompressibility of the oil, thus relieving the pots and the conductor glands of the necessity of withstanding pressures up to 1,200 pounds per square inch. However, the castor oil has a cubical temperature coefficient of expansion of approximately ten times that of the Everdur metal making up the pot, and a temperature rise of 30 degrees Fahrenheit would cause the oil in one pot to attempt an expansion of about seven cubic inches, which is resisted, would build up an internal pressure of about 2,500 pounds per square inch. Therefore it is necessary to provide means whereby the oil can expand and contract with temperature changes. A Sylphon bellows is installed in the sled for this purpose, accommodating large volume changes in the oil with pressure differentials of a few tenths of a pound per square inch.

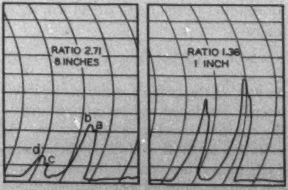

Figure 8. Recorded crossings of cable

Left—Eight inches; right—one inch

The towing cable having a breaking strength of 14 long tons (2,240 pounds to the ton), is especially designed for the purpose of towing the sled and carrying the detecting coil connections to the cable ship. It has as its main feature torsional balance, that is, the towing cable will not twist appreciably when load is applied. To accomplish this, there are two layers of steel wires 0.05 inch in diameter, the inner layer having 44 wires laid up right hand, with the second or outer layer of 50 wires laid up left hand. The messenger pair consists of two conductors twisted together so as to form a complete transposition every two inches. This steel towing cable is spliced on to bronze wire ropes 40 feet ahead of the sled to avoid the generation of signals in the detecting coils due to relative motion between the steel towing cable and the sled. There is also a second possibility for interference in the steel towing cable. Magnetic flux from poles formed on the steel wires will thread through the space between the two electrical conductors, and a change in this flux will generate a potential in the circuit. This type of interference occurs only when the tension in the steel towing cable is suddenly increased or decreased, and is of no importance during normal towing operations.

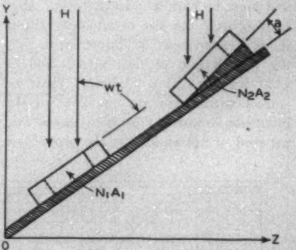

Figure 9. Theory of balancing

The apparatus must be prepared to make a chart record of signals varying widely in magnitude. As the peak signal generated in the detecting coils varies roughly as one over the distance squared, an ocean cable which will operate the re-

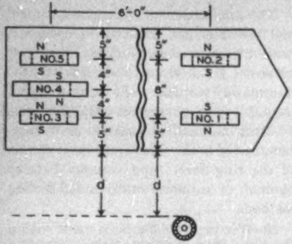

Figure 10. Depthometer coil arrangement

cording apparatus full scale at zero inches from the sled bottom (5 inches from the lower coil inside the sled), will give only seven per cent at 15 inches from the sled bottom. The accurate recording of such a wide range is impracticable. To provide a means whereby the smallest signals can be accurately read, and still prevent the maximum signal from exceeding 100 per cent or going off scale, recourse is had to a so-called "exponential amplifier," in which the output voltage of the amplifier varies as some root of the input voltage. Stated algebraically:

$$e_o = k\sqrt[n]{e_i}$$

where e_o is the amplifier output voltage, e_i the input voltage, and n positive and greater than unity. The general procedure is to rectify the signal after four stages of amplification, filter, and apply to various combinations of the control and suppressor grids of the first two stages of the amplifier. Application of this controlling direct voltage must be rapid enough to control the signal which brought it about; at the same time, too rapid a control will cause low-frequency oscillation.

The extremely low level of signal available at the input of the amplifier requires greater than usual precautions. The maximum signal obtainable from the type of cable used in the plowing is 0.3×10^{-6} amperes through the amplifier input resistance of 50 ohms, or 15×10^{-6} volts. The interference level from bumping of the sled along the bottom, tube noises in the amplifier, interrupter contact noise, etc., is around 6×10^{-9} amperes or 0.3×10^{-6} volts. The contacts of the interrupter are brought together and separated by a cam mechanism, making higher contact bearing pressures possible, which assists in reducing noise. The input transformer which has its low-voltage winding in series with the detecting coils and the interrupter, requires a triple iron magnetic shield to guard against stray changing magnetic fields and also the effect of the ship's rolling and pitching in the earth's magnetic field. A change in the amount of flux threading through the primary winding of the transformer is as productive of potentials as if the change took place through the detecting coils.

The expression for the maximum voltage developed in a single detecting coil of N turns and an average area of A centimeters squared, rotating at the rate of f cycles per second through the earth's field H is as follows:

$$E_{\max} = 2\pi f N A H \times 10^{-8}$$

where

NA = 25,380 turn inches squared = 163,700 turn centimeters squared
H = approximately 0.5 maxwell per square centimeter, the total intensity of the earth's field
f = approximately 0.5 cycles per second, the rate at which the coils were turned in the process of balancing

then

$$E_{\max} = 2\pi(1/2)\ 163{,}700 \times 0.5 \times 10^{-8} = 0.0026 \text{ volts}$$

This is the value then of the voltage developed by a single detecting coil. In order to reduce this voltage from 0.0026 to the desired interference level of 0.3×10^{-6}, the second differentially connected balancing coil must develop an $E_{\max}$ within 0.3×10^{-6} divided by 0.0026 or one part in 8,667 of the $E_{\max}$ of the first coil. This calculated figure of roughly one part in 9,000 compares favorably with the experimentally determined value of one part in 12,000. The net maximum rate of change of magnetic flux density through the two differentially connected detecting coils to produce a signal of 0.3 microvolts, the interference level, is 1.8×10^{-4} maxwells per square centimeter per second.

Operation of the depthometer on ocean cables of various histories has brought out the important fact that the plowing operation causes a considerable drop in the magnetization of the cable, which however, is recovered to a great extent in the first year. The loss is probably due to the bending and "working" of the cable in passing over various sheaves on both the cable ship and the cable plow, and ranges in value from one-half to two-thirds of what may be called the ultimate magnetization of the cable sheath. In other words, recently plowed cables exhibit magnetizations of from one-third to one-half of that found in cables laid a number of years previously.

Although the depthometer was intended originally for use in the special application of measuring the depth to which ocean cables had been buried, it has been found very useful in locating ocean cables[2] and in obviating the danger of "hooking" the wrong cable when cloudy skies or dim horizons prevent the taking of accurate navigational sights, or when an error made at the time that the cable was laid appears on the chart in a manner additive to that of the observational sight taken at the time of subsequent repairs. By the use of the detecting feature of the depthometer, the relative positions of two or more cables in a particular locality may be determined, after which grappling operations may be conducted with comparative safety.

The experience of two years' work with this measuring and detecting device has demonstrated its usefulness in both the special application of measuring the depth of burial of ocean cables and also the routine application of locating cables prior to repair operations. The practicability of constructing and balancing the detecting coils so that they may be dragged along ocean bottoms has been demonstrated, together with the ability of the d-c amplifier and interrupter to operate in the field at electrical levels usually thought of as strictly for the laboratory.

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2. PROTECTION OF SUBMARINE CABLES BY PLACEMENT "UNDERGROUND," ELECTRICAL ENGINEERING, volume 57, May 1938, page 204.

Remote-Control Toll Board

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THE ESSENTIAL operating facilities placed at the disposal of toll operators for the switching and completion of long-distance calls have, in a general sense, remained substantially unchanged since the early days of toll switching. It is still common practice, in toll offices, to have toll lines and local subscribers' trunks terminate in multiple jacks and lamp signals with associated cords and plugs to permit the operator to answer and extend calls between local stations and stations at distant toll centers. In addition, toll operators are still dependent on the assistance of inward and through operators for connecting within and through distant toll centers.

As toll systems become more complex due to the extension of the system and development of new services, with the complexity of operating routines to meet the ever increasing demand for service and speed, there is a general tendency toward the adoption of new switching methods, such as combined line and recording, even though these methods require the toll operator to give a greater amount of undivided attention to each call during the build-up period. Experience has demonstrated that with this service, a greater number of operators are required, especially during peak hour periods, to accept and extend toll calls without undue delay.

Another factor which has become important in recent years is the widespread use of toll dialing for the extending and completion of outward toll calls, even in exchanges using cord-type boards. This method of operation, requiring that operators use different procedures on the various types of calls, make it more difficult to train operators, and inevitably increases the likelihood of error.

Development of the remote-control toll board has made it possible to retain the advantages of these new methods of toll operation, and at the same time achieve a real saving in time and labor. Placing before the toll operator more efficient switching facilities enables her to receive and clear toll calls more rapidly, thereby vitally affecting both operating and plant costs. In many cases, the resulting increased line efficiency will avoid the need for new circuits which would otherwise be required to reduce subscriber and operator waiting time until the circuits become available.

The remote-control toll board, together with its associated electromechanical switches, is complete in itself for the switching of toll within its own office, as normally completed by means of toll boards of the cord type. In addition, it incorporates features to facilitate the completion of calls by the originating toll operator to stations within and through distant toll offices. Associated with each toll board are groups of finders which automatically extend incoming calls to idle operators. Simplified links, key senders of the quick-action push-button type, supervisory lamps and keys, together with primary and secondary outgoing selectors, give toll operators access via key-sender method, to both toll and local stations.

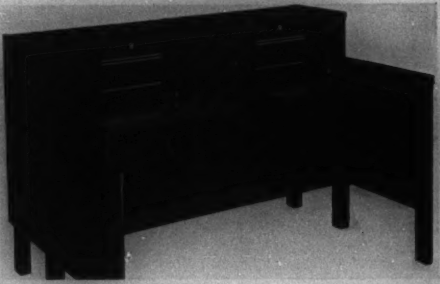
Figure 1. Remote-control toll switchboard section

While outgoing selectors are provided for the remote-control toll board, their use is not confined to this board alone. The switches are grouped, to form what could be considered a toll automatic exchange with trunk channels connecting to the associated local central-office equipment. Distant toll boards, either of the remote-control type or of the cord type, when equipped with automatic dial trunks and repeaters may, if desired, make use of toll automatic exchange switches.

The application of the remote-control toll board is not confined to operation with Strowger central offices, since by means of trunk groups and repeaters, the automatic switches will operate with varied types of central-office systems, whether manual, automatic, or a combination of both. Line equipment can be of the ring-down type, common-battery manual, or automatic with varied dialing methods.

Notable progress has been made within the last two decades in converting metropolitan, suburban, and rural exchange areas to automatic operation. Paralleling this development, there has been a strong tendency to provide dialing methods to handle the complex suburban toll traffic within large metropolitan toll areas. Small urban areas and rural communities have likewise grown into comprehensive short-haul toll networks utilizing various forms of dial tandem operation. In such networks, provision for direct calling between subscribers is utilized to quite an extent when such calls can be set on a predetermined meter rate basis. Likewise, various forms of automatic timing are being increasingly employed to permit direct dialing between local and distant automatic exchanges thereby eliminating the need of going through a toll switchboard with operator supervision. Calls which cannot well be placed on a predetermined rate or automatic timing basis must of necessity be handled by toll operators and it is for such traffic that the remote-control toll board has been designed.

A number of automatic networks involving long-haul toll lines have been placed in service with very satisfying results. With the assistance of improved toll switching equipment, more efficient means are provided for the speedier handling of calls over automatic switching networks. Heretofore, automatic network dialing has been retarded due to the

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use of dialing trunks added to existing manual boards as an applique unit and using ordinary dials, in lieu of modern trunk selection or specially designed boards equipped with sending equipment capable of sending both long and short call numbers without delaying the short call numbers.

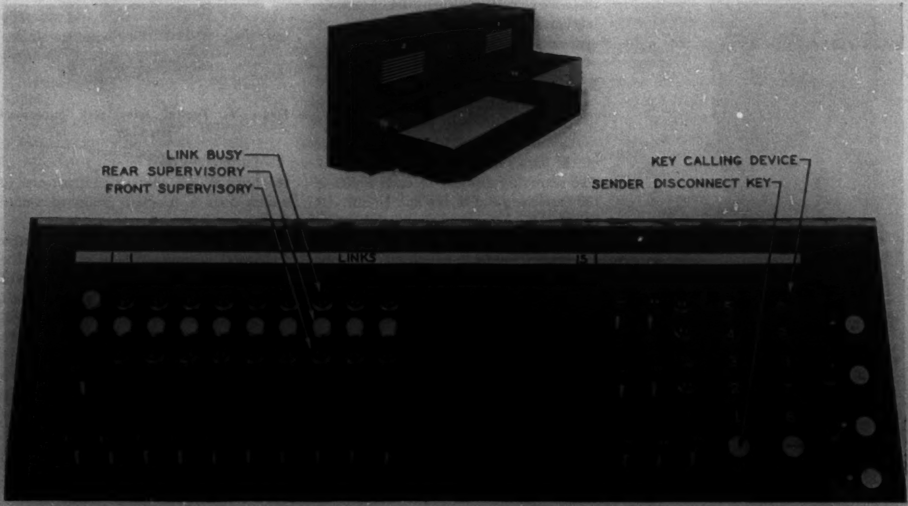
Principle of Operation

Briefly, the remote-control toll board provides for connections from local subscribers to toll, toll to local subscribers, and toll to toll by means of electromechanical switches under the control of toll operators. Incoming calls, either from trunk or toll lines, terminate on the banks of a finder switch. A signal received over any line or trunk automatically causes a finder to operate and connect to the calling line. This call is immediately connected to an idle operator's headset, at which time the operator receives a double impulse of high-frequency tone, commonly called "zip-zip" tone. Upon being informed of the desired toll station, the operator sets up the toll group code by depressing digit keys in her key-sender set. The operation of digit keys causes a preselector, which is tied direct to the finder, to select a nonbusy line within the group dialed. The operator, by means of a link circuit (which corresponds to a cord circuit in the ordinary type of toll board) supervises connections and does the necessary ticket timing.

Physical Equipment

The physical equipment consists of operators' switchboard equipment shown in figure 1. The key shelves of this switchboard are equipped with a variable number of links and associated keys and lamps in quantities dependent on position loads. The detail of a key shelf together with its associated turret is pictured in figure 2. It will be seen from this figure that each link consists of a talk and monitor key, a front supervisory lamp, a rear supervisory lamp, and a link busy lamp. To the left of these keys are located certain common keys and lamps. These, together with other keys and lamps to the right of link circuits, are termed "common equipment." This common equipment is connected to each link talk key and automatically becomes a part of any link on which the talk key is operated. Operating practices provide for only one talk key being operated at one time. Equipment located in the turret of each operator's position consists of group identity and group busy lamps in addition to space for toll tickets. No equipment other than that indicated on this position key shelf and turret layout is mounted in the operator's position switchboard. All coils, capacitors, relays, and switches are located in a separate automatic equipment room to permit ease of maintenance and systematic routining without disturbing operators. Associated with each link is a line finder switch (shown in figure 3). In common with other switches of this type, the finder consists of three banks of contacts at the bottom, a vertically located shaft with spring "wipers" at the lower end, and electromagnets near the middle which can lift and rotate the shaft and wipers to any desired set of bank contacts. At the top are relays which control the electromagnets and other circuits. This finder provides for lines and trunks to be connected to its banks. The function of the finder is to hunt a line or trunk on which a call has been received, causing the switch to step up and across the bank to seize the calling line or trunk, the contacts of which were "marked." This finder connects directly to link talk keys by means of switching relays and to an outgoing preselector. The preselector is a two-motion switch very similar to the finder. Its operation, however, is under the control of key-sender equipment and control keys 0 to 9 pictured to the right in figure 2. The wipers of this switch respond in a vertical direction to the bank level corresponding to the key depressed by the operator. The rotary action is automatic. It passes over busy lines or trunks but stops and switches through on the first nonbusy line or trunk. Subsequent keys depressed on the key sender will operate other ranks of selectors similar to the preselector in order to obtain subline and trunk groups. With the aid of similar

Figure 2. Typical key-shelf and turret arrangement



stepping switches in connecting toll centers, the local or answering toll operator is able to control the selection of lines, trunks, and subscriber stations without the assistance of an inward or through operator.

Relays associated with the positional keys, likewise with trunks and lines, are mounted in units and assembled on frameworks as shown in figure 4. Figure 5 shows four relay units with covers removed. These are completely wired self-contained units arranged for bolting to horizontal relay rack angles. Outgoing leads from each unit terminate on pin block terminals to facilitate production, installation, and maintenance. Key-sender equipment employs similar groups of relays for the storage and sending of digits registered through the operation of keys in the key sender. Rotary switches for the automatic association of an idle sender and storage relays with link keys are shown in figure 4 immediately above the relay groups.

Functions of the Toll Operator

The prime purpose of toll switching equipment is to provide a medium for toll operators to receive, extend, supervise, and time calls from local subscribers to subscribers served by distant toll centers. It is quite obvious that the type of equipment should be of such a design as will permit rapid and efficient service to the toll user with the minimum amount of operator effort in performing mere mechanical functions in setting up and supervising talking circuits. The method most commonly used in completing toll calls enables subscribers in local offices to reach the toll operator over a recording trunk from the local switchboard or in the case of automatic, by the subscriber dialing a long-distance code and terminating on a combined line and recording trunk within the toll board. Calls received over recording trunks are extended by the operator to toll lines connecting to distant toll points by means of cord circuits. These calls are extended with the aid of inward and through operators in other connecting toll centers and finally to the called subscriber while the originating or calling subscriber waits on the line.

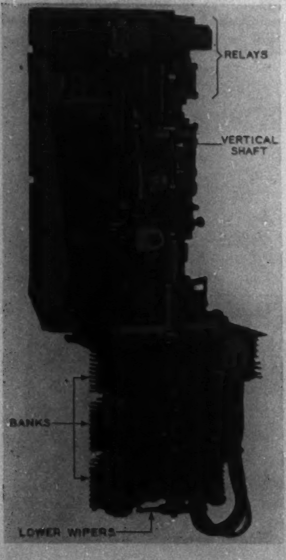


Figure 3. Finder switch

The procedure on the remote-control toll board enables subscriber to reach the toll board by means of a manual trunk in the case of manual exchanges or by dialing a long-distance code in the case of automatic offices. These calls instead of being answered by the use of plugs and cords, are automatically received on an idle operator's headset, at which time a "zip-zip" tone is received by the operator. Calls are extended by dialing toll group code numbers, causing the seizure of an idle toll line to the connecting toll center. With toll switching facilities in distant toll centers, the originating operator can readily complete calls by means of the regular key sender to subscribers in the distant exchanges without delay in waiting for assistance by inward and through operators.

Line and Trunk Finder and Link Circuit

Incoming lines and trunks terminate on the banks of finder switches, figure 3. The searching element of each finder is the answering end of the link circuit. It is connected by means of a switching relay to a talk and monitoring key and three supervisory lamps at one of the toll positions. One lamp serves as a link busy indication. The other two are answering and calling supervisory lamps as in standard cord board practice. A toll preselector is permanently associated with the calling end of each link circuit for extending calls into the trunking system. Each operator's position is equipped with several link circuits, the exact number depending upon the type of service to be handled. Present practice ordinarily provides for inward positions to be wired for 18 links, CLR (combined line recording) positions for 6 to 8 links, and delayed positions for 5 links.

Two general groups of finders are usually provided except for the smaller installations, one serving the inward positions and the other the CLR and delayed-call positions. Special groups of lines or trunks may be terminated at specialized positions by providing separate finder groups for the segregated lines or trunks or by arranging the finders associated with the links in the specialized positions to search over a selected group of finder bank contacts.

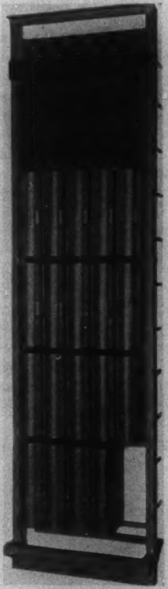


Figure 4. Typical relay rack equipment assembly

Operators indicate their preparedness to receive incoming calls by operating the talk key of a nonbusy link. Operation of a link talk key prepares the associated link circuit for receiving an incoming call and connects the link to the operator's position circuit. Incoming calls then are received automatically on the operator's headset. The presence of a call on the link is indicated by a double impulse of high-frequency tone ("zip-zip" tone) in the operator's receiver. The origin of incoming calls is indicated by the lighting of a line or trunk group identity lamp.

This identity lamp lights in the answering position only and remains lighted during the period the link talk key is operated.

Operation of the link monitoring key enables the operator to listen in on established connections without disturbing conversation. With two monitoring keys thrown, the operator can monitor on both connections. With one monitor and one talk key thrown, the operator may listen and talk on both connections, but can ring, dial, split, and release only on the link on which the talk key is operated. This feature permits the overlapping of certain operations on two connections in accordance with standard toll operating practices.

Supervisory relays are placed in the line and trunk circuits instead of the link circuits, permitting the same simplicity of link circuit design and equipment economies as are afforded by the latest type cord boards.

Position Circuit

The remote-control toll board uses a position circuit which includes common equipment such as transferring, splitting, ringing, dialing, and releasing keys and associated relays. Under normal talking conditions, the answering end of the link is connected to the calling end of the switching equipment, free from shunts or attachments, without looping through the toll switchboard. By operation of the talking key associated with the link circuit, the position circuit is connected between the answering and calling ends of the link and the operator's set is connected across the link.

With the talking key of any link circuit operated, the operator may:

(*a*). Dial on the answering or calling end of the link.

(*b*). Split the talking circuit between the answering and calling ends of the link.

(*c*). Release either or both ends of the link.

(*d*). Transfer "out of order" toll lines to the toll test board.

(*e*). Ring on the answering or calling end of the link.

On calls to local stations from inward positions, the ringing is automatic. On calls to local stations from CLR and delayed positions, the ringing is automatic only after the ringing key is operated to start the ringing. Thus, local lines may be seized and ringing delayed while the toll circuit is being built up.

A common splitting key is provided by means of which the operator may talk to the subscriber on either end of the link without the other subscriber overhearing. Release keys are provided by means of which the answering or calling ends of the link may be released separately or both ends may be released simultaneously. All position circuit keys function only when the talk key of a link circuit is operated.

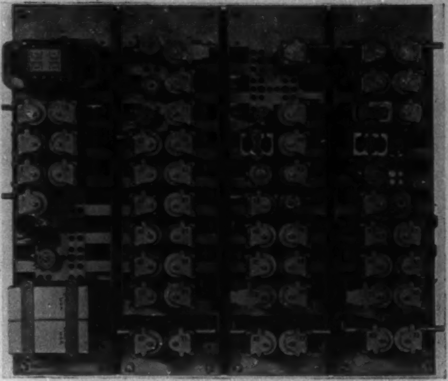


Figure 5. Operators' position relays

Link and Sender Finder Equipment

Each operator's link and sender finder equipment consists of a relay group, which is part of the position circuit, and four 6-level 25-point rotary switches. Figure 6 shows a link and sender finder rotary switch group for four switchboard positions. Four rotary line switches are associated with each position. Two of the rotary switches provide two separate channels to the common group of senders and the other two extend the sender channels through to the particular links on which the operator throws her talk key. Two sender channels are provided so that the operator may overlap sending on two connections. Circuits are so arranged that the sender is locked to the link until all digits are sent out, even though the operator may restore the link talk key. Operation of a second link talk key will cause seizure of the second sender channel and permit the operator to set up another connection while the first sender is still functioning on the connection previously set up.

The rotary switch shown in figure 7 consists chiefly of two parts, a rotary mechanism and a bank assembly. The rotary mechanism is composed of a motor magnet with spring assembly, rotary pawl, ratchet wheel, and wiper assembly.

When the motor magnet is energized, its armature pulls up. Near the end of its stroke, the break contacts of its own interrupter springs open and breaks the circuit to the motor magnet. The motor magnet de-energizes and its armature falls back, stepping the wiper assembly around one contact. When the motor magnet restores, its interrupter springs again make contact, and if further rotation is required, the circuit to the motor magnet is again closed. The rotary pawl is attached to the armature. It is drawn away from the pawl stop when the armature pulls up, and under tension of a small spring attached to it, falls into the next tooth of the ratchet wheel. When the armature falls back, the rotary pawl is pushed in toward the armature stop by the force of the tension spring, and the ratchet wheel to which the wipers are attached is caused to rotate on its axis.

The ratchet and armature pawl arrangement prevents the ratchet wheel from making any movement except under control of the rotary armature.

The wipers are double-ended, making contact with either end, and are of special design to give flexibility and good contact.

The construction of the bank is such that one end or the other of the wipers will at all times be in engagement with a set of bank contacts, the second set of wipers coming into action when the first one leaves the last set of the bank contacts.

Commutator brushes project from the bank assembly and make continuous contact with the wipers.

Sender and link finder switches both use six-level banks and six pairs of wipers.

The operation of a link talk key marks one of the link finder bank contacts, and the wiper assembly will rotate until the wipers are opposite the marked bank con-

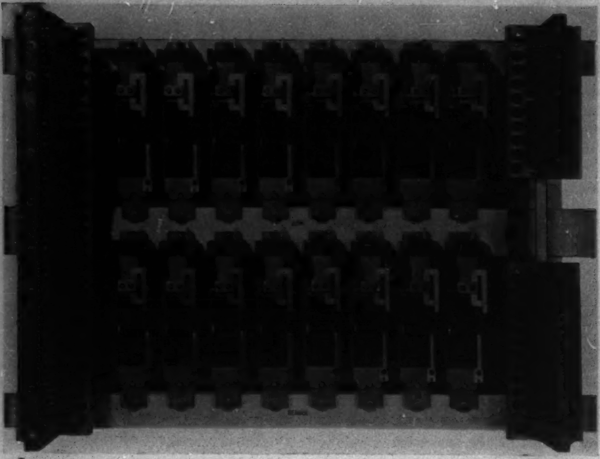


Figure 6. Link and sender finder switches

tact, thereby connecting the sender control relays with the particular link, the talk key of which has been thrown. Simultaneously the sender finder wipers rotate until they find a marked sender finder bank contact, thereby connecting an idle sender through the sender control equipment to the link circuit having the talk key thrown.

Common-Start Position-Distributing and Level-Distributing Equipment

Since separate line and trunk finder switch groups are furnished for each operator's position, common-start equipment is provided to limit the search for an incoming call to one finder switch only. Several operators may be waiting for calls at any given instant, therefore, position-distributing equipment is also provided to distribute incoming calls to the waiting operators in a definite sequence. A level-distributing circuit is also provided to prevent line and trunk finder switches from selecting waiting calls from the lower levels of their banks in preference to those on the upper levels. This circuit functions to distribute the incoming calls in sequence according to the bank levels on which they are received. The combined functioning of the start and distributing circuits provides effective teamwork by enforcing an even distribution of all incoming calls to those operators who are prepared to receive them, and by eliminating all wasted effort usually caused by several operators attempting to answer incoming signals that have several multiple appearances.

Digit Registers and Sender Equipment

A common group of register and sender units is provided. This group is accessible to all operators through the action of rotary finders, thus providing for their economical use since they are used for only a short period during each call. The registration equipment is reflexive in that an unlimited number of digits may be registered with a comparatively few storage groups. This is accomplished by using the digit registers over and over in their respective order after they perform their functions. The register and sender equipment is connected to the link until the operator depresses the sender disconnect key, thereby providing for any tandem dialing conditions that may be encountered in existing or ultimate networks. The sender releases digits within the storage sets without waiting for the complete registration of call numbers. The sender equipment consists of relay groups and is designed to mount on toll trunk relay racks.

Switching Layout

Schematic diagram, figure 8, shows the grouping of circuits with paths connected for a toll-to-toll call, using toll group call number 44. This figure also shows the paths to a local automatic station as on a toll-to-local call using local station number 6384.

Figure 9 shows a similar layout as required for a large multioffice system, with various types of toll line selectors to meet the conditions imposed by different sizes and classifications of toll line groups.

Through Call—Toll to Toll

On a typical through call, the distant operator rings on the toll line causing a ring-down relay to operate and place a marking potential on the associated finder bank contact. The finder switch associated with the operated talk key of a nonbusy inward operator's link automatically begins to search for the marked bank contact, stepping vertically to the bank level on which the marked line is located and horizontally until the marked bank contact is found.

The functioning of the common-start and position-distributing equipment permits only one finder to search for the incoming call. When the finder wipers reach the bank contacts of the calling line, the horizontal motion of the finder switch is stopped and relay operations extend the toll line to the operator's position equipment. Further relay action in the operator's position equipment causes a seizure indication in the form of a "zip-zip" tone to be impressed on the operator's headset, thereby informing her that a call has been received and is ready to be answered. In case no operator is waiting, the call will be held in abeyance and a common answering pilot lamp will light in all positions, as a signal that one or more calls are waiting for operator's service. After a predetermined time interval, a master lamp lights in the chief operator's desk indicating that a call is being delayed. This master lamp flashes after a further predetermined time to draw to the attention of the chief operator a need for closer supervision, or increased operating personnel to guard against delay in serving toll subscribers. Any operator becoming free will throw the talk key of a nonbusy link and the call will be automatically connected to her headset.

One set of bank contacts on the finder switches associates the incoming lines with the group indicating lamps at the toll switchboard. Relay operations in the finder cause the proper toll-group-identity lamp to light automatically, identifying the toll center from which the call originated. The group identity contacts on the finder banks are not multiplied between operators' finder groups; therefore, the identity lamp lights only in the position at which the call was received. Finder relay operations cause the link busy lamp to light when the calling line is seized. This busy lamp remains lighted for the duration of the call to provide for supervision and to guard against attempted reuse of the link until the call is released. As soon as the finder has completed its vertical stepping, circuit conditions are set up in the link and sender finder relays which cause the sender finder to search for an idle impulse sender and digit register group, and for the link finder switch to search for the particular link on which the operator has her talk key thrown.

When an idle sender is connected to the link, the sender supervisory lamp lights, indicating to the operator that an idle sender and digit register group is connected to the front end of the link in readiness for setting up, on the key calling device, the group code of the desired toll center. After acknowledging the call and receiving the order, the operator depresses the digit keys of the calling device in accordance with the number of the desired toll circuit group and depresses the sender disconnect key. Operation of the numeral calling device keys, which are connected to the digit register group through the link and sender relays, causes corresponding digits to be stored in the digit register relay groups in the same order that the keys were depressed.

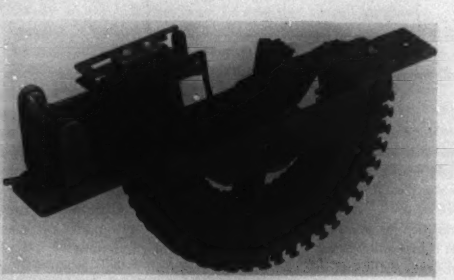


Figure 7. Rotary switch

The impulse sender begins sending as soon as the first digit key is depressed and continues as long as any digits remain stored in the digit register relay groups. Preselectors and subsequent switches respond to impulses released by sender and digit register relay groups.

On the typical toll call shown in figure 8, the operator dials 44. The first digit 4 causes the preselector to step to its fourth level and automatically rotate and stop on a nonbusy toll line selector trunk. The second digit 4 causes the toll line selector to step to its fourth level and select an idle toll line.

Depressing the sender disconnect key serves as an indication to the sender equipment that no further digits will be registered and prepares the circuit for disconnect from the link after all stored digits have been sent out. When the switches have completed their functions, relay operations in the sender finder relay group extinguish the supervisory lamp and automatically disconnect the impulse sender from the link, thereby making it available to other operators.

When the sender supervisory lamp goes out, the operator rings on the toll line by throwing her "ring-front" key. Relay operations in the toll line relay group cause the proper ringing frequency to be impressed on the toll line. The terminating toll operator, on answering, may now talk to the originating operator with the remote control operator bridged across the line. At the start of toll conversation, the operator restores the link talk key causing a relay to restore in the link circuit. This relay disconnects the common position circuit from the link, making it available for use on other links.

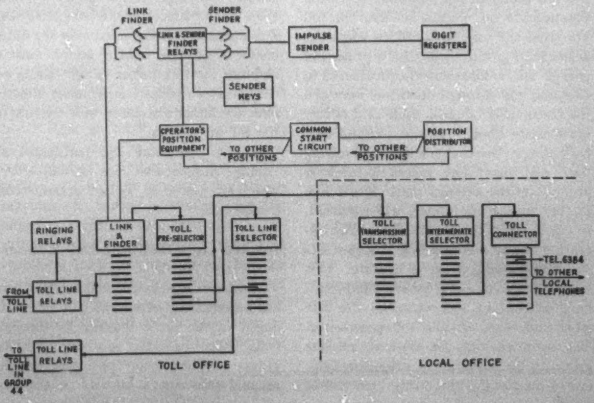
The toll group identity lamp also goes out when the talk key is restored.

When the originating operator rings off on the toll line, relays in both originating and terminating toll line relay groups operate, causing the white and red supervisory lamps of the link circuit to light. The operator throws the link talk key (or link monitoring key in case she is busy on another call) and challenges. With the talk key thrown, relay action in the link circuit reconnects the operator's position equipment to the link. The toll group identity lamp relights, identifying the originating office.

The operator rings off on the front end of the link with the "ring-front" key, giving the terminating operator disconnect supervision. With the talk key still operated, the operator clears the link and connecting circuits by operating a common link release or wipe-out key causing the supervisory lamps, link busy lamp, and toll group identity lamp to go out and the link and trunk circuits to restore to normal. If, upon clearing a call, the operator is ready to receive a new call, the link talk key is left operated; otherwise, it is restored to normal.

When all lines to a desired toll point are busy, a chain relay circuit is closed in the toll line relay groups causing a toll group busy lamp, located in the face panel, adjacent to the identity lamp, to light in all positions. The operator observing this busy lamp delays dialing to that particular toll group in accordance with standard operating practices. Absence of a lighted group busy lamp indicates that a toll circuit is available. Should

Figure 8. Call through schematic toll-to-toll and toll-to-local calls



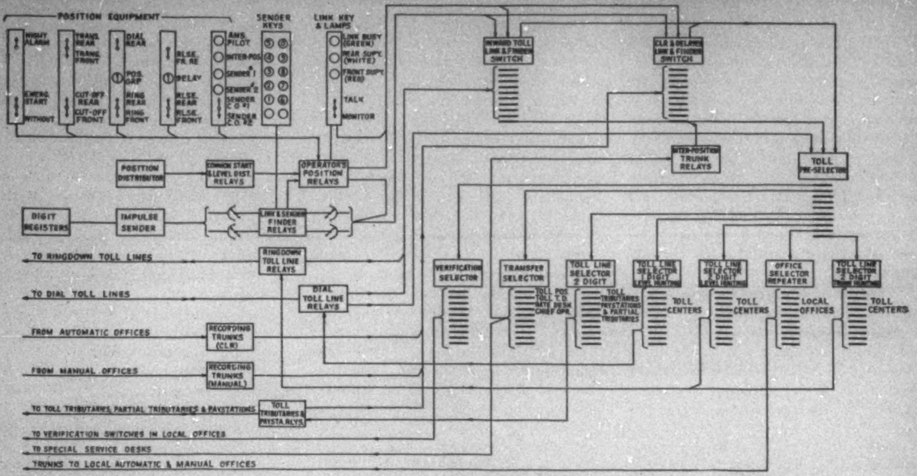

POSITION EQUIPMENT
NIGHT ALARM
EMERG. START
WITHOUT
TRANS. REAR
TRANS. FRONT
CUT-OFF REAR
CUT-OFF FRONT
DIAL REAR
POS. GRP
RING REAR
RING FRONT
RLSE. FR. RE
DELAY
RLSE. REAR
RLSE. FRONT
ANS. PILOT
INTER-POS
SENDER 1
SENDER 2
SENDER C.O. #1
SENDER C.O. #2
SENDER KEYS
5 0
4 9
3 8
2 7
1 6
LINK KEY & LAMPS
LINK BUSY (GREEN)
REAR SUPY. (WHITE)
FRONT SUPY. (RED)
TALK
MONITOR
POSITION DISTRIBUTOR
COMMON START & LEVEL DIST. RELAYS
OPERATOR'S POSITION RELAYS
DIGIT REGISTERS
IMPULSE SENDER
LINK & SENDER FINDER RELAYS
TO RINGDOWN TOLL LINES
RINGDOWN TOLL LINE RELAYS
TO DIAL TOLL LINES
DIAL TOLL LINE RELAYS
FROM AUTOMATIC OFFICES
RECORDING TRUNKS (CLR)
FROM MANUAL OFFICES
RECORDING TRUNKS (MANUAL)
TO TOLL TRIBUTARIES, PARTIAL TRIBUTARIES & PAYSTATIONS
TOLL TRIBUTARIES & PAYSTA. RLYS.
TO VERIFICATION SWITCHES IN LOCAL OFFICES
TO SPECIAL SERVICE DESKS
TRUNKS TO LOCAL AUTOMATIC & MANUAL OFFICES
INWARD TOLL LINK & FINDER SWITCH
CLR & DELAYED LINK & FINDER SWITCH
INTER-POSITION TRUNK RELAYS
TOLL PRE-SELECTOR
VERIFICATION SELECTOR
TRANSFER SELECTOR
TOLL POS
TOLL T.D.
RATE DESK
CHIEF OPR.
TOLL LINE SELECTOR 2 DIGIT
TOLL TRIBUTARIES PAYSTATIONS & PARTIAL TRIBUTARIES
TOLL LINE SELECTOR 1 DIGIT LEVEL HUNTING
TOLL CENTERS
TOLL LINE SELECTOR 2 DIGIT LEVEL HUNTING
TOLL CENTERS
OFFICE SELECTOR REPEATER
LOCAL OFFICES
TOLL LINE SELECTOR 2 DIGIT TRUNK HUNTING
TOLL CENTERS

Figure 9. Typical toll-switching diagram

the operator fail to observe the busy indication, or should the toll group become busy during her dialing period, relay operations in the toll line selector cause the link supervisory lamp to flash at a rate of 120 impulses per minute. In this event, the front end of the link is released by operating the "release-front" key thereby restoring it to condition for redialing the toll point or for completion by dialing an alternate route.

In case "all paths busy" condition is encountered in the automatic switches prior to reaching the desired toll line group, the trunk switch will rotate to the 11th position of the busy bank level and operate its cam springs causing the link supervisory lamp to flash at a rate of 60 impulses per minute (to differentiate from the toll group busy). In case operating practices do not permit holding the toll line from the originating office when the desired toll group is busy for a prolonged period, the remote control operator, or in this case the through operator, may call the originating office as soon as a circuit becomes available. This is accomplished by dialing on the rear of a link. Throwing the "dial rear" key places a marking ground on the vertical bank of the line finder, causing the finder, when started, to cut in on its first bank level. The operation of any nonbusy link talk key sets its corresponding finder to operate. This finder, due to marking by the "dial rear" key, will cut in and rotate on the first level and seize an idle toll preselector. The operator dials the desired toll line group to the terminating office, then operates the ringing key on the rear end of the link and restores the "dial rear" key. When the distant operator answers, the operator dials the originating office on the front end of the link as previously described.

To permit dialing on the rear of a link, certain leads from the operator's position equipment are terminated on a set of bank contacts on the rotary switch of the link finder. When the "dial rear" key and a link talk key are operated, this set of bank contacts is marked and the link finder switch rotates to these position circuit contacts instead of searching for the link. Simultaneously, the sender finder rotary switch seizes an idle impulse sender and digit relays group. When these circuit functions are completed, the impulse sender is extended over the bank contacts of the sender finder switch, through the link finder switch banks, to the operator's position equipment; thence, over the finder associated with the link to the toll preselector.

Similar operations are performed at "delay" positions to care for call orders which are passed to "delay" operators for completion.

Inward Call—Toll to Local Manual

Inward calls to local manual subscribers are automatically received and acknowledged in the same manner as through calls. The operator sets up an office group selecting code plus the desired manual subscriber's number on the key sending set and depresses the sender disconnect key. Automatic switches cause the local number to be displayed at the manual-exchange call indicator position by way of a call indicator trunk. The link talk key may be restored immediately after the sender disconnect key is depressed. The sender supervisory lamp goes out when the automatic switches have completed their functions.

The call indicator operator plugs into the multiple jack of the called line, if idle, and ringing starts automatically. The front supervisory lamp of the link circuit lights when the line is taken up by the call indicator operator and is extinguished when the local subscriber answers. Conversation starts and the inward operator restores the link talk key, if not previously restored, extinguishing the toll group identity lamp. The operator may monitor by operating the link monitoring key.

Supervision is obtained by the local subscriber restoring the receiver which causes the front supervisory lamp to light and the distant operator ringing on the toll line lights the rear supervisory lamp. The operator throws the link talk key or link monitoring key (in case she is busy on another call) and challenges. With the talk key thrown, the toll group identity lamp relights, identifying the originating toll office.

To disconnect, the inward operator clears the link and connecting circuits by operating the link release or "wipe out" key causing the supervisory lamps, link busy, and toll group identity lamps to go out and the line equipment to restore to normal in readiness to receive a new call.

The call indicator trunk disconnect lamp lights, giving disconnect supervision to the call indicator operator.

When the manual-exchange subscriber's line is busy, the call indicator operator will press a busy key causing the link supervisory lamp to flash at 120 impulses per minute. In this event, the front end of the link is released by operating the "release-front" key, thereby preparing it to redial the manual exchange number. "All paths busy" as on automatic trunks is indicated by a 60-impulse-per-minute flashing link supervisory lamp.

Local Automatic to Ring-Down Toll (CLR)

A local automatic subscriber dialing the long-distance directory code is received by one of the waiting CLR operators who has a nonbusy link key thrown to the talk position. In case no operator is waiting for a call, the incoming call will be held in abeyance with the lighting of the common answering lamp in toll positions and the master lamp in the chief operator's desk as described for through calls. The first idle operator will throw the talk key of any nonbusy link. Seizure tone will be heard the instant the call is connected to her link circuit and the link busy lamp will light. The CLR trunk group identity lamp will also light, indicating the origin of the call. The sender supervisory lamp will light indicating that an idle sender is connected to the link.

After acknowledging the subscriber's order and making a toll ticket, the operator sets up the desired toll circuit on the key sending set and depresses the sender disconnect key. The sender lamp goes out when the automatic switches complete their functions, and the operator throws the "ring front" key to ring on the toll line. The called number is passed to the distant operator and conversation starts when the called party answers. The operator starts timing the ticket and restores the link talk key, extinguishing the CLR trunk group identity lamp. When the local party restores his receiver, the rear link supervisory lamp lights. The operator throws the link talk key (or link monitoring key in case of overlap operation when a talk key is operated on another link), challenges, and stamps the stop time on the ticket. The operator rings on the toll line with the "ring front" key giving the distant operator disconnect supervision. Disconnect operations and line and trunk busy indications are the same as previously described.

If the local party dialing the directory code is in a denied-toll group, the high-frequency seizure tone is followed by a splash of lower-frequency tone. This indicates to the operator that toll service shall be denied to the calling party. If the operator is in doubt as to hearing the denied-service tone, she may cause it to return by operating the "ring rear" key.

Local Manual to Toll, Utilizing Call-Indicator Equipment

The manual-exchange subscriber, removing his receiver, signals the *A* board operator and on a request for "long distance," the *A* operator plugs into an idle recording trunk jack. The CLR (combined line recording) operator receives and acknowledges the call in the same manner as previously described for local automatic-to-toll calls. In addition, since incoming calls from manual exchanges on the CLR method cannot be extended direct to a toll line due to lack of switchhook supervision from the calling party through the manual *A*-position cord circuit, it is necessary that means be provided to permit the CLR operator to reach the calling subscriber over an outgoing trunk from the toll board. The CLR operator, on receiving a call, instructs the calling subscriber to wait on the line and restores the talking key. An idle link key is then operated together with two positional keys termed "dial rear" and "without" keys. The operator sets up the manual office code on her key sender followed by the calling subscriber's number. The subscriber's number is displayed on the call indicator display panel in the usual way but, due to the circuit condition prepared through the action of the "without" key, the associated call-indicator supervisory trunk lamp flashes. This flashing lamp is an indication to the call indicator operator that the call is CLR from toll and that connection should be made to the called line without making the customary busy test. This "without" key is used only on CLR calls where it is intended to disregard busy. It is not used in the completion of inward or delayed calls. Upon reaching the calling subscriber over the outgoing trunk as described above, the calling party is transferred to a toll switching trunk thereby permitting the operator to receive switchhook supervision from the calling party. From this point, the call is handled in the same manner as previously described in connection with local automatic-to-toll calls.

Release of the CLR trunk on which the call was originally received is accomplished by operating the link talk key and "release-rear" key. The *A* operator may be recalled on this trunk any time prior to its release by operating the "ring rear" key intermittently. The *A* operator may recall the toll operator by plugging in and out of the jack.

Delayed Calls

Calls to certain towns, and calls which cannot be completed immediately by CLR operators, are handled on a delayed ticket basis. Tickets for such calls are passed from CLR positions to point-to-point operators.

The point-to-point operator throws the "dial rear" key and establishes connection with the calling subscriber on the rear end of the link by setting up, on her key calling device, the office code plus the subscriber's number. Upon her restoring the "dial rear" key, a sender is automatically connected to the front end of the link, and connection is established with the desired toll line by dialing the proper code. When the distant operator answers, the operator passes the called subscriber's numbers. When the called party answers, the operator rings the calling subscriber by throwing the "ring rear" key. Supervision, timing, disconnect, and busy indications are the same as previously described.

Direct Dialing to Distant Toll Offices

Calls to direct-dialing toll offices, whether originating at the local exchange or switching through it, are handled as explained under the respective preceding methods of operation with the following exceptions.

The local toll operator (inward, CLR, or delayed) in calling the distant exchange number sets up the distant office code followed by the subscriber's number. A flashing supervisory signal is received when the called line is busy or a steady supervisory signal when the called line is free. Ringing of the distant party starts automatically. If the call passes through intermediate automatic exchanges, the operator sets up the code of the intermediate office and awaits dial tone. As soon as dial tone is heard, she sets up the code of the terminating office and then the subscriber's number as previously described.

To reach points beyond direct dialing points, the local toll operator sets up the exchange code and rings. This signals the inward operator at the direct dialing point who acts as a through operator in the standard manner.

Calls Transferred From One Toll Position to Another

The nature of certain classes of calls requires that they be transferred to operators' positions other than those on which the calls are received. The receiving operator may transfer a call to any other position by dialing the required operator code on the front end of the link. This causes the call to be extended to an interposition trunk in the position to which the call should be transferred. An interposition trunk answering lamp will light when the trunk is seized as an indication to the operator that a transfer call is waiting. If the operator should be waiting for a call with a link talk key operated, the call will be received immediately on her headset.

Circuits are so arranged that interposition trunks are given preferential selection when the operator throws a link talk key. On inward and CLR positions, interposition calls are answered before any other waiting calls can be received. On delayed positions they are answered before the operator can originate further calls.

Discussion

B. C. Bellows (Bell Telephone Laboratories, Inc., New York, N. Y.): We are in full agreement with the idea implied in the paper that present toll switchboards should be readily adaptable to the future requirements which seem to indicate clearly a higher degree of mechanization in the toll switching facilities. This requirement has already manifested itself as illustrated by the fact that approximately ten per cent of the present Bell System operator-handled toll traffic is on a dialing basis not requiring the aid of inward or through operators for completion. While we are not entirely familiar with the conditions for which the remote-control cordless toll board was designed we believe it would be of interest to make a few comments on the paper presented, based on Bell System experience.

In so far as Bell System experience is concerned the type of toll switchboards provided today are similar to those provided in the "early days" in appearance only. The present Bell System modern outward toll boards while still of the cord and jack type, are substantially improved from a circuit and equipment standpoint. These improvements include such things as the automatic inclusion of repeater gain at switching centers where this is required, cord circuits arranged for common-battery supervision, dialing or key pulsing on both cords of a cord pair, improved transmission, improved signaling and key equipments, as well as many other miscellaneous improvements making for a more satisfactory operating arrangement.

As far as we can see, the introduction of the combined-line-recording method has had no bearing on the relative advantages of cord and cordless toll boards. Experience in the Bell System has demonstrated that the combined line and recording method requires slightly fewer operators than with previous methods. This is due to the fact that previous operating practices followed in the Bell System required toll operators to give the same undivided attention to the call in hand as is required with the combined-line-recording method, which procedure was justified because of the improved service and greater intertoll trunk efficiency that was thereby obtained.

Present Bell System cord boards are designed to permit dialing or key pulsing and common-battery supervision on both ends of the cord circuits, and are, therefore, readily adaptable to intertoll dialing requirements. There are, of course, inherent differences between the ring-down and intertoll dialing methods of operation. These fundamental differences would appear to be present regardless of the type of toll board employed. Bell System experience indicates that these different procedures do not unduly complicate the operator training and there has been no indication that an increase in operating errors is to be expected.

In the continuous effort that is being made to provide improved facilities, consideration has been given to cordless toll boards for Bell System use. This consideration has indicated that only in the handling of inward and through connections is the cordless toll board of substantially greater efficiency than cord boards. The possibilities for economies on outward boards would seem to lie in the elimination of cord handling and double answering. However, it has been our experience that on outward positions cord handling is so small a part of the operator's work time as to be hardly measurable and double answering occurs in any appreciable amount only when several operators are idle under which condition there is no noticeable effect on operating efficiency. To meet the recognized advantages in the handling of inward and through traffic, a cordless toll board employing crossbar switches is being made available.

Gilbert Sorber and Arthur Bessey Smith: We are glad for the remarks by B. C. Bellows, of the Bell Telephone Laboratories, and to note that he is in substantial agreement with us.

It is quite generally recognized that toll boards of today differ materially in circuit design from earlier types of toll boards. Even so, the continued use of plugs and jacks places a very definite limitation on the design of operators' working equipment. With the remote-control toll board it has been possible to design the operators' equipment to meet operators' requirements instead of being strongly influenced by the mechanical limitations of plugs and jacks.

We have not held that the introduction of the CLR (combined-line-recording) method has any direct bearing on the relative advantages of cord or remote-control types of toll boards. We do, however, point out that the type of toll board has a direct bearing on the grade of service to subscribers when the CLR method of operation is used. The remote-control toll board improves the grade of service to subscribers, because it enables the operator to give a greater amount of undivided time to the call in hand.

Inherent differences exist between the ring-down and intertoll dialing method of operation, but the design of the remote-control toll board provides improved facilities for meeting the changes in operating methods which result from these inherent differences.

The increased efficiency which results from the use of the remote-control toll board, when considered on a position basis only, is, we agree, most noticeable on inward traffic. Our experience with actual installations, however, indicates surprisingly enough that because of the greater number of positions involved, the over-all saving in outward traffic is even greater than on inward traffic.

Power Supply for Single-Phase Resistance Welders

R. H. WRIGHT
MEMBER AIEE

THE rapidly increasing use of a-c contact welders in metal fabricating plants imposes single-phase low-power-factor fluctuating loads on plant power systems. The loads may range from a few kilovolt-amperes for a few cycles per weld, as in the case of a small spot welder, up to several thousand kilovolt-amperes for five to ten seconds per weld in the case of a large butt welder. Where the plant is supplied from a small private generating station, single-phase welding loads not only cause troublesome voltage fluctuations but may damage the damper windings of the generators. If power is purchased from a utility, voltage fluctuations may still be present, not only in the plant but often in the entire adjacent area. To eliminate such disturbances it has been necessary in numerous instances to install motor generators to serve as phase converters to supply single-phase power. It is the purpose of this paper to discuss the more common applications for single-phase welding generators and the electrical problems involved in each type of application.

The principal applications for conversion equipment are in connection with butt, flash, spot, and seam welders, and tube welding machines.

Butt Welder

Among the earliest installations of single-phase generators for welding service were two motor-driven units for supplying butt welders used in fabricating automobile rear-axle housings. The original generators for this installation were old engine-type alternators which had been rewound for single-phase service. The normal capacity of the generators was small relative to the welding load and the machines had to be heavily over excited during the welding period. The main circuit between the generator and the welder was closed and opened for each weld. The generator windings vibrated excessively under load and if the main circuit was opened accidentally during a weld, high open-circuit voltages were developed; resulting in bus insulator flashovers and damage to the generator windings. Under such conditions an undue amount of maintenance was required. Operation was improved materially by changing to generator field control. Later modern equipment of greater capacity was installed which has given continuous service with only routine maintenance.

Figure 1 shows the type of weld made in such machines. The welding time varies from five to eight seconds. The generator output varies from 6,000 to 9,000 amperes at 350 to 400 volts, depending on the weight of the stock welded. In figure 2 are shown typical curves of voltage and current input to a rear-axle-housing butt welder. Two recent single-phase generators for this service are rated at 6,500 amperes, 440 volts, 60 cycles, 2,860 kva. Another generator used for the same purpose has a rating of 10,000/5,000 amperes, 220/440 volts, 2,200 kva, 60 cycles.

A schematic diagram of connections of a recent equipment is shown in figure 3. The generator is connected continuously to the primary of the welding transformer; circuit breakers in the main leads being used only for short-circuit protection. Complete control of the welding cycle is obtained by a field contactor and a field rheostat. No automatic voltage-regulating equipment is required as the load is quite stable during the weld. Only infrequent adjustments are required to compensate for changes in welding conditions.

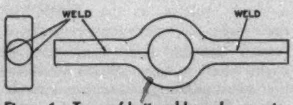


Figure 1. Type of butt welds made on automobile rear-axle housings

Generators for this class of service can be driven satisfactorily by synchronous motors. Where it has been desired to reduce the line peaks or reduce the rate of change of input, wound-rotor induction motors with flywheels have been used. A fixed slip resistance provides a satisfactory means of equalizing the peaks.

Flash Welders

One of the most common functions of the larger flash welders is to weld sheets or plates together at the edges. A large variety of products may have one or more welds made in this way. The two plates to be welded are clamped in the welding machine with the edges parallel. The edges are then brought together lightly and power is applied. Arcing and burning of the metal occurs uniformly throughout the length of the joint and the two pieces are heated rapidly for a short distance back from the line of contact. The two parts of the machine advance slowly together to compensate for the metal which is thrown off or consumed. At the end of the heating period the power is cut off and a quick acting cam forces the two edges together to make the weld.

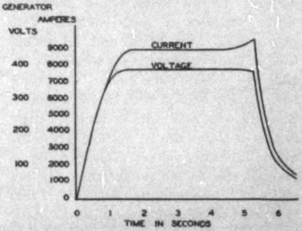


Figure 2. Typical single-phase load on a butt welder for automobile rear-axle housings

The time for making flash welds varies with the thickness of the metal and the amount of power which can be applied without the formation of blowholes. About 10 to 15 seconds is common for many applications involving heavier material. During the early part of the heating period, while irregularities in the edges of the stock are being burned off, the load is light. As the heating extends over the entire length of the weld the load rises rapidly to a maximum and fluctuates violently.

Power is usually controlled by a contactor in the primary circuit of the welder transformer. For many flash-welding operations it is not necessary to use a voltage regulator to maintain satisfactory generator voltage. In such cases generator field forcing is used. Between welds

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the generator excitation is only sufficient to give approximately full voltage at no load. A field-forcing contactor interlocked with the main welder contactor, shunts a portion of the generator field resistance at the start of the heating period. The voltage variation during the heating period is thus limited to less than five per cent. At the end of the heating period the field-forcing contactor opens and normal no-load excitation is restored. Where it is felt that closer regulation of voltage is required to give the desired uniformity of welds, a voltage regulator and quick-response excitation system can be used.

In figure 4 are shown graphic charts of the voltage and kilowatts output of a 500-kva 400-kw single-phase generator which supplies a flash welder. Two plates 0.107 inch thick and 80 inches long at the weld were being welded at the time the charts were made. Generator field forcing is used with this equipment. Starting with 485 volts at no load, there is first a slight dip in voltage when the main contactor closes, followed by a gradual rise to 509 volts when the full effect of field forcing is obtained. From this point to the end of the weld the maximum voltage variation is 3 per cent with load variations from approximately 35 per cent of generator capacity to approximately 80 per cent capacity.

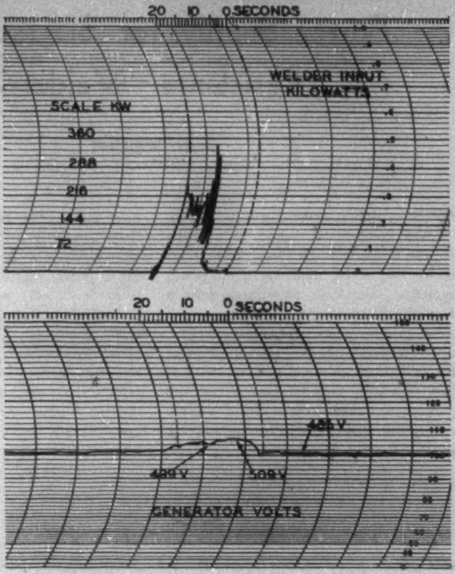

Figure 4. Kilowatts output and voltage of a single-phase generator operating in conjunction with a flash welder

Generator field forced during welding period

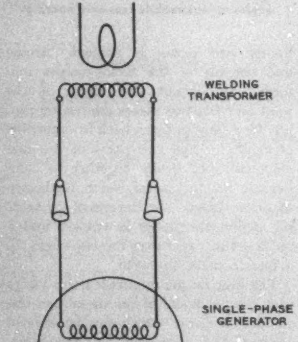

Figure 3. Schematic diagram of connections used for single-phase generators supplying large butt welders

The motor generator for which the curves are shown has a synchronous driving motor, so the load fluctuations are reflected directly to the power lines. Power is supplied by a small local central station. While the load peaks are quite evident on the station chart, no difficulty is experienced in maintaining a steady voltage on the system. In cases where the welder imposes peaks of several thousand kilovolt-amperes, it might be advantageous to use an induction motor and flywheel to iron out the violent fluctuations and limit the input to an average value. However, in the majority of applications, a synchronous driving motor will be quite satisfactory.

Spot and Seam Welders

Spot and seam welders usually operate in conjunction with timers which definitely fix the duration and energy input for each weld. Usually the time for each weld varies from one cycle to 12 or 15 cycles. With spot welders the welds are made at random as desired by the operator and the power impulses follow no definite pattern. The load on the circuit supplying a seam welder consists of a succession of short impulses repeated at regular intervals. Electronic timers are in quite general use for both spot and seam welders.

Because of the peculiar nature of the load, generators which supply single-phase power to spot and seam welders operate under conditions which are quite different from butt-welding and flash-welding service. In spot-welding service it is impracticable to use generator-field-forcing contactors because of the very short duration of the welding peaks. Also generator voltage regulators are of little or no value for the same reason. Single-phase generators for supplying spot welders are, therefore, designed so that the normal capacity is approximately equal to the welding peak loads. The transient voltage drop and the inherent voltage drop at full load are made to be approximately equal. The excitation is kept constant at a value which will give the desired voltage during the weld. In figure 5 are reproductions of oscillograms showing typical load conditions on a 700-kva single-phase generator which supplies a spot welder. The oscillograms show how the generator voltage drops instantly when load is applied and remains constant during the welding period.

In spot-welding service the welding time is only a very small percentage of the total time, so the root-mean-square loads

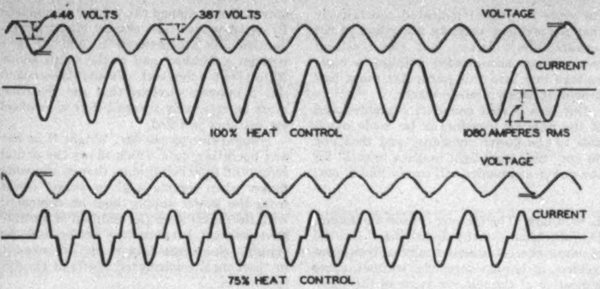

Figure 5. Oscillograms of typical spot-welding loads on a 700-kva 440-volt 30-per-cent-power-factor 60-cycle single-phase generator

Timing and energy input are controlled by an electronic timer

on the generator and its driving motor are very moderate. If a synchronous driving motor were used, the capacity would be determined largely by the magnitude of the peaks received from the generator. It may be possible for the frequency of the load pulsations to be the same as the natural period of oscillation of the set. Such a resonant condition may cause a synchronous driving motor to pull out of step unless special precautions are taken. For these reasons it is more satisfactory to use an induction motor to drive a generator used for spot-welding service. A squirrel-cage motor with a small amount of slip will utilize the flywheel effect of the set to equalize the peaks and insure stable operation. In extreme cases a small amount of additional flywheel effect can be built into the set. Figure 6 shows a 700-kva 0.30-power-factor single-phase spot-welding generator with a 150-horsepower squirrel-cage driving motor.

A motor generator which is to be used for supplying a seam welder will operate under steadier load conditions. A larger motor will be required to carry the higher average loads. Either a squirrel-cage motor or a synchronous motor will be satisfactory. In many cases it will be advantageous to use a voltage regulator with the generator to insure uniform welds. The regulator will maintain a definite average voltage which will be the average between the unregulated no-load and full-load voltages.

Tube Welders

Certain kinds of thin-walled tubing may be made by passing long coils of steel strip at constant speed through a forming and welding machine. Either alternating current or direct current at low voltage can be applied to the welding rolls. Where alternating current is used it may be advantageous to use a frequency higher than that of the regular supply circuit. A motor generator with a single-phase generator of the desired frequency is then required. Close voltage regulation is essential, so voltage regulators are used. Since the load is steady and practically continuous and speed variations should be minimized, a synchronous motor gives the most satisfactory drive.

Conclusion

The problem of power supply for high-capacity single-phase welding circuits has come into general prominence only recently. However, over a period of several years past, motor-driven single-phase generators have been installed for practically every type of welding service. Experience gained from these installations provides a basis for the correct application of conversion equipment for future requirements.

Figure 6. Single-phase 700-kva 0.30-power-factor welding generator with 150-horsepower squirrel-cage driving motor

It is desirable to make each installation as simple as possible and experience has shown that extremely simple apparatus gives excellent service for many applications. It is preferable to use generators with specially designed single-phase windings rather than to use one phase of a three-phase machine. Because of the vibration inherent in single-phase machines, it is highly desirable to avoid working welding generators at high overloads. Also the voltage can be controlled more readily when the peak loads are not greatly in excess of the normal capacity of the generator. The rated power factor of welding generators will range from 30 per cent for spot welders to 60–70 per cent for butt and flash welders.

There are some applications for which it is desirable to operate more than one welder from a single generator. Two or more spot welders with electronic timers can be operated from a single generator of minimum capacity if an electronic synchronizing device is used which permits only one welder to be energized at one time. Such an arrangement introduces no appreciable delay in production since each welder in turn is locked out only a fraction of a second. At least one installation is in successful operation where two welders are operated simultaneously from one generator. Each welder is controlled by a contactor and each main contactor is interlocked with a field-forcing contactor so that the generator field strength is approximately proportional to the load.

Discussion

B. M. Jones (Duquesne Light Company, Pittsburgh, Pa.): We, in Pittsburgh, have a great number of welder installations on our system, and we are getting more of them and they are becoming larger in size; and we believe that electric welding is going to be used more and more because it is an efficient, practical, convenient tool.

As you may know, a power company's concern over welders is the fear that the fluctuating load may cause a flicker in the lights of adjacent customers, which may be, and sometimes is, objectionable. Therefore, it is our job to "tool up" the system in the vicinity of the particular welder to prevent such fluctuating loads from affecting the lighting load to an extent that would be objectionable. Obviously, a slow reduction in voltage to quite an appreciable lowering of the normal voltage and then a gradual return to normal is not so perceptible and is very rarely objectionable, whereas an abrupt lowering of voltage, even to a much less degree than the slow reduction, is perceptible and would very likely become objectionable.

Another point the power company must investigate carefully is the amount of transformer capacity necessary to deliver suitable voltage to make a successful weld—in simple language, the regulation of the transformer. This, in most cases involving medium size and large welders, is a more important factor than the heating effect. A typical example encountered on our system recently was a large welder causing a 250-kva single-phase heating load and requiring a 667-kva transformer to hold the voltage sufficiently close to permit a successful weld. Naturally, this resulted in a larger investment. We have three or four such welders at different plants, and in each case have installed a 667-kva transformer for the 250-kva heating load.

In one of these installations, it developed that the three-phase power bank supplying the rest of the customer's plant had sufficient margin of capacity to carry this 250-kva heating load, but the voltage dips on the main bus with this welder connected thereto would have been of the order of 18 to 20 per cent, and it was felt that this would result in objectionable performance of the customer's motors, such as tripping them off, due to low voltage or sudden change in loads. It was therefore decided to install the 667-kva single-phase transformer for the welding load alone.

Other difficulties we have encountered have been with welders connected to our four-kv three-phase distribution system on the basis of the welding transformer characteristics as shown partially on the name plate, and then after the welder has been placed in service we find that the resulting swings are much greater. In several cases this differential has been so great that we were forced to provide a high tension line for the welder. Actually, in one specific case, we obtained from the welder manufacturer complete electrical characteristics of the transformer, *and then* the performance (by tests we made) indicated conclusively that the welders were not according to the manufacturer's letter, and the resultant large swings necessitated building a high-voltage line into this particular plant and providing larger transformers.

Our plea is that complete characteristics of the welding transformer be made available to the power company, and that you do not "hide your light under a bushel" for the power companies will surely find it out!

L. W. Clark (The Detroit Edison Company, Detroit, Mich.): Any discussion of the use of motor generator sets for serving resistance welders is hardly complete without some indication of the relative value of the three different types of sets in shielding the power-supply system from voltage disturbances. Whenever it becomes necessary to consider a motor generator set, it is usually because the welder, if served direct from the supply system, will cause a disturbing lamp flicker. It thus becomes necessary to install a set that will reduce this flicker to a value not objectionable.

The type of set which will accomplish this at the lowest first cost and operating expense should be selected. It is true that a flywheel induction set is the most effective in eliminating the voltage disturbance, but in most cases I believe it will be found that it does a much better job than is actually necessary. Likewise, the straight induction set without the flywheel is more effective than a synchronous set, but if the synchronous set accomplishes all that is necessary, its high operating power factor usually makes it the logical selection.

Most industrial plants, particularly those using large numbers of welders, need some form of power-factor correction to keep their overall plant power factor within reasonable and economical limits. Both the straight induction set and the flywheel set not only offer no improvement in this regard but actually reduce the plant power factor. The synchronous set, on the other hand, while doing a good job of flicker reduction also pays a return on its investment in the form of plant-power-factor improvement.

Some preliminary calculations on a proposed installation indicate that the introduction of a synchronous set will reduce the flicker caused by a welder in the ratio of between 4 and 8 to 1, the actual ratio depending upon the characteristics of the motor and also the ratio of resistance to reactance in the supply circuit. Assuming that a specific installation showed an improvement in the ratio of 6 to 1, the synchronous set would satisfactorily correct a flicker condition in which the welder, if served direct, dipped the voltage as much as 10 or 12 volts. The similar ratios for induction sets are between 10 and 30 to 1 without a flywheel and in the range above 30 to 1 with a flywheel. From this comparison it appears obvious that the situation must be extremely severe before a flywheel set becomes justified.

I would like to ask Mr. Wright if he has any operating data which shows the actual *before* and *after* conditions, that is, the volts flicker when serving a given welder direct from the power supply lines as compared with the flicker after the addition of a motor generator set between the welder and the supply. Such test data would be valuable in checking the calculated effects of the different sets.

R. H. Wright: Mr. Clark's position regarding the use of flywheels on welding motor generators is in general the same as that of the author. Flywheels are useful only for special applications. Two rather large welding sets with flywheels and induction-motor drive are operating in Detroit on purchased power. When the sets were built, the purchasers felt that flywheels should be incorporated so as to reduce the peaks if it ever became necessary to operate on the plant generating system. When operating on central-station power the reduction of load peaks is of little advantage and synchronous drives would be quite satisfactory and would give the advantages of a higher operating power factor.

Flywheel sets can be used to advantage when power is to be taken from a small d-c generating station. The flywheel will insure steadier speed than can be obtained with a d-c motor alone.

No tests have been made to indicate the improvement in voltage resulting from the transfer of a welder from the power lines to a motor generator.

The matter of momentary peak loads imposed by resistance welding machines, as discussed by Mr. Jones, is very important regardless of the source of power. For most types of welders the load is applied and released instantaneously and the power factor is low. This condition gives the maximum lamp flicker when the welder is connected directly to distribution lines. In calculating the effect of a welding load on the voltage regulation of a given circuit it is necessary to consider the duty cycle of the welder as well as the name-plate rating. Welders which are designed for intermittent duty may draw peaks of 300 per cent of the name-plate rating. Some indication on the name plate of the maximum peak capacity would be of great value.

Effect of Corona Discharge on Liquid Dielectrics

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THE proper functioning of a high percentage of electrical equipment depends on electrical insulating mediums, such as oils, under conditions known to include corona discharge. This is particularly true in the case of high-voltage cables of the "solid" type.

As early as 1917, Clark and Shanklin[1] published curves of resistivity versus voltage for paper-insulated cables at low temperatures, and attributed the erratic nature of these curves to gaseous ionization occurring in voids in the insulation. Less than two years later, Shanklin and Matson[2] discussed the ionization of occluded gases in high-voltage insulation quite extensively. In their paper, mention was made of some chemical analyses of the deteriorated material deposited on the walls of the gas spaces. A great deal of work followed in which various aspects of corona in voids in dielectrics were studied. In 1924, a paper was presented by Del Mar and Hanson[3] and much of the ensuing discussion of the paper concerned a wax-like substance, which they termed X, which had been found in oil-impregnated paper cables after they had been subjected to high electrical stresses. Some tests were described by E. R. Thomas[4] in which cable impregnating compounds had been subjected to corona discharge in the laboratory with the result that a yellow waxy substance with numerous void spaces was formed which was termed "Swiss cheese." Similar tests were later reported by Farmer[5] and by Willman.[6] It appeared evident then that the wax-like substance, X, was the result of a condensation of the oil molecules due to the action of the gaseous electric discharge. Schoepfle and Connell[7] undertook a careful review of the literature on this subject and concluded that the same reactions of hydrocarbons were produced by both the corona discharge and the alpha particle. Their studies of the effect of cathode rays on hydrocarbon oils showed that cathode rays also had to be classed in this category.

There was at that time considerable information available in the literature regarding the chemical changes brought about in hydrocarbons by electrical bombardment, but there was a distinct lack of knowledge with respect to the changes occurring in the electrical characteristics of hydrocarbons. In most of the investigations that had been conducted, a type of discharge different from corona discharge was used, or the hydrocarbons involved were gaseous at atmospheric conditions, or the effects studied were concerned with chemical changes only. In the present studies, which were started late in 1930, use was made of a corona discharge cell, which could be expected to simulate closely the discharges occurring in the highly stressed insulation of a-c equipment in commercial use. The materials studied were oils, such as liquid paraffin, cable oils, and hydrocarbons of various known types of molecular structures. The main purpose of the studies was to investigate what changes, if any, occur in the electrical characteristics of liquid dielectrics due to corona discharge. Changes in their chemical and physical characteristics were also investigated in the hope of uncovering any relations which might exist between these characteristics and their changes due to corona discharge.

TEST EQUIPMENT AND METHOD

Two test cells which were used in these studies are shown in figures 1 and 2. The cell shown in figure 1, designated as cell 1, was designed to incorporate the features of having the oil sample between layers of solid dielectrics while being subjected to corona discharge, and between metal electrodes while its electrical characteristics were being measured. This cell was also designed to be self-contained in order to eliminate possibilities of contamination of the sample during transfer from bombardment chamber to measuring chamber. The transfer of the sample was accomplished by means of automatic circulation of the oil, a feature used by Becker[8] in his studies on the transformation of hydrocarbons. Figure 1 shows a cross section of the cell as it appears during operation. With voltage applied between electrodes E_1 and E_2 and a Sprengel pump connected to stopcock V, bubbles form in the oil in discharge chamber D, and are drawn through connecting tube T_1 into measuring chamber M. Here the bubbles burst, liberating the gas to be pumped off and releasing the oil to mix with that in the measuring chamber from which it eventually returns to the bombardment chamber through tube T_2. The bombardment may be stopped at any time and measurements may be made to obtain the electrical characteristics of the oil.

Table I. Data on Test Cells

Cell 1: Measuring cell	
Outside diameter of active electrode (inches)	1.000
Length of active electrode (inches)	8.000
Inside diameter of high-voltage electrode (inches)	1.200
Thickness of test sample (inch)	0.100
Thickness of mica washers (inch)	0.030
Cell constant A/L (centimeters)	709
Capacity of cell with air dielectric (micro-microfarads)	63.5
Bombardment chamber	
Inside diameter of inner tube (millimeters)	21.4
Outside diameter of inner tube (millimeters)	25.4
Inside diameter of outer tube (millimeters)	30.4
Outside diameter of outer tube (millimeters)	34.4
Thickness of bombardment space (millimeters)	2.5
Length of bombardment electrode (inches)	8.000
Amount of oil necessary, per run (milliliters)	550
Cell 2: Measuring cell	
Diameter of active electrode (inches)	2.000
Width of guard ring (inch)	0.208
Spacing between active electrode and guard ring (inch)	0.003
Spacing between active and high voltage electrodes (inch)	0.010
Cell constant A/L (centimeters)	1596
Capacity of cell with air dielectric (micro-microfarads)	141
Amount of oil necessary to fill measuring cell (milliliters)	5
Bombardment chamber	
Size of gas accommodation bulb (liters)	2
Outside diameter of inner bulb of bombardment chamber (millimeters)	37
Inside diameter of outer bulb of bombardment chamber (millimeters)	42
Space between inner and outer bulb (millimeters)	2.5
Wall thickness of glass (millimeters)	2

Note: All metal parts of cells 1 and 2 heavily gold plated.

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This work formed part of an investigation on the deterioration of high-voltage underground cable conducted by The Detroit Edison Company under the direction of the late Doctor C. F. Hirshfeld, chief of research. It was made possible only by the co-operation of the staff of the research department, and the aid and advice of many people not connected with the department. Thanks are offered to all, and in particular to Doctor C. S. Schoepfle, professor of organic chemistry at the University of Michigan, who served as a consultant, and to C. D. Robb and A. G. Fleiger of The Detroit Edison Company research department, who made most of the measurements and determinations involved.

1. For all numbered references, see list at end of paper.

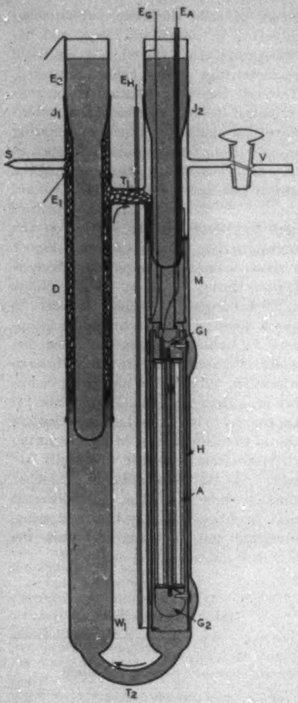


Figure 1. Cell 1 for corona discharge and for power-factor and conductivity determinations

A—Active electrode
D—Discharge chamber
E_1—Graphited bombardment electrode
E_2—Silvered bombardment electrode
E_A—Connection to active electrode
E_G—Connection to guard circuit
E_H—Connection to high-potential electrode
G_1, G_2—Parts of guard circuit
H—High potential electrode
J_1, J_2—Ground joints
M—Measuring chamber
S—Seal-off tube
T_1—Top connecting chamber
T_2—Bottom connecting tube
V—Stopcock
W_1—Support for measuring cell and connection to high-voltage electrode

Cell 1 was used in the preliminary tests on oils of which large amounts were available. Later, when hydrocarbons of which large amounts were not readily available were studied, the cell shown in figure 2, designated as cell 2, was used. Its main parts are the cell for electrical measurements *E*, the bombardment chamber *A*, and the gas accommodation bulb *B*. Incorporation of these three parts in one cell renders it self-contained to a high degree. The volume of the bombardment chamber is large compared with the volume of the oil sample; that is, all of the oil is in the bombardment chamber during the bombardment period, which renders superfluous any extra means for keeping the oil in circulation. The oil is transferred to the measuring cell by turning the whole cell upside down. The volume of the gas accommodation bulb is sufficient to avoid pressure changes of objectionable magnitude in the cell from gas produced during normal periods of bombardment. This makes unnecessary the removal of gas from the cell during the bombardment period and enables omission of liquid air traps necessary in the line to the Sprengel pump used with the previous cell. Pertinent dimensions and constants of both test cells are given in table I.

In the tests with cell 1, the samples were subjected to two bombardment periods, each of $6^1/_2$ hours duration. The gases evolved in the first one-half hour of each bombardment period were used to flush the entire vacuum system and then discarded; those evolved during the remaining six hours were pumped off continuously by means of a Sprengel pump and stored in a gas-collecting bottle. A Schering bridge was used for the power factor measurements which were made at 4,750 volts, 60 cycles (average stress of 47.5 volts per mil). In the tests with cell 2, the samples were subjected to one bombardment period of four hours duration. The evolved gases were accumulated in the cell and were pumped off after the bombardment period by means of a Toepler pump. A transformer bridge, similar to that described by Doyle and Salter,[9] was used for the power factor measurements which were made at 200 volts, 60 cycles (stress 20 volts per mil). In a number of special test runs, the test conditions were changed to suit the particular needs. Measurements of power factor, d-c resistance, and other electrical characteristics were made at various temperatures before bombardment and after each bombardment period. In some cases, attempts were made to measure the current in the corona discharge. Dielectric strength determinations were also made in a few instances on samples before and after bombardment. The amount of gas liberated during bombardment and the composition of the gas were determined in the majority of all tests. In a number of cases, determinations were made, before and after bombardment, of iodine number, hydrophil content, and viscosity.

Compounds Tested

The materials studied were pure liquid paraffin oils, various cable oils, and ten hydrocarbons of known types of molecular structure. The cable oils and certain samples of the liquid paraffin were used as received, except for drying and degassing. The other compounds were procured as pure as possible, but some had to be treated chemically to purify them further; all were distilled in a good vacuum at low temperatures. Pertinent information regarding the samples is given in table II. After the samples were prepared for test, they were protected from coming into contact with the atmosphere by being transferred either directly into the highly evacuated test cell or into

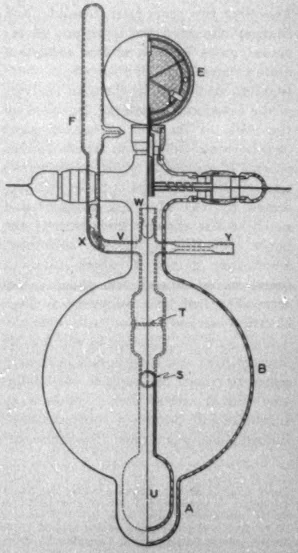


Figure 2. Cell 2 for corona discharge and for power-factor and conductivity determinations

A—Discharge chamber
B—Gas accommodation bulb
E—Cell for electrical measurements
F—Sample container
S—Main offtake tube
T—Sillimanite filter
U—Silvered bombardment electrode
V—Offtake for sample container
W—Offtake for removal of gas
X—Glass-enclosed magnetically operated hammer
Y—Seal-off tube

Table II. Oil Samples and Their Treatment Before Test

Samples				Treatment				
					Distillation			
Name of Compound	Designation	Formula or Base	Source	Initial	Kind of Still	Temperature	Pressure	Residue
n-hexadecane	*A*	$C_{16}H_{34}$	Eastman Kodak Co., Eastman grade	None	Hickman	Degassing coil at room temperature Distilling column at 80 deg C	Between 0.1 and 0.2 micron Hg	Very small percentage
n-hexadecene	*B*	$C_{16}H_{32}$	Synthesized from cetyl alcohol at University of Michigan	Treated with metallic sodium	Hickman	About same as n-hexadecane		
Synthetic oil number 4530*a* (hydrogenated 4530)	*C*	Mixture of saturated branched chain hydrocarbons	Synthesized by hydrogenation of 4530 and 4555 respectively at temperatures up to 200 deg C and pressures up to 200 atmospheres, Ni catalyst, at University of Wisconsin	None	Hickman	Removal during distillation of small amounts of methylcyclohexane introduced during hydrogenation process. Otherwise about the same as the corresponding unhydrogenated oils.		
Synthetic oil number 4555*a* (hydrogenated 4555)	*D*							
Synthetic oil number 4530	*E*	Mixture of unsaturated branched chain hydrocarbons. Molecular weight—610 for *E;* 944 for *F*	Standard Oil Co. (Indiana)	None	Hickman	Degassing coil below 125 deg C Distilling column about 185 deg C	0.01 micron Hg gas pressure	About 50 per cent of starting material
Synthetic oil number 4555	*F*					Degassing coil below 150 deg C Distilling column at 320 deg C		About 20 per cent of starting material
Decalin (decahydronaphthalene)	*G*	$C_{10}H_{18}$	Eastman Kodak Co., practical grade	Several days over sodium, then centrifuged and filtered	Conventional high-vaccum still	Distillation bulb at room temperature. Receiver at −80 deg C	0.01 micron Hg gas pressure	About 1 per cent of starting material
Turpentine polymer (synthetic)	*H*	Mixture of unsaturated cyclic hydrocarbons	Turpentine polymerized with $AlCl_3$	None	Hickman	Degassing coil at room temperature Distilling column at 100 deg C	Between 0.1 and 1.0 micron Hg	About 20 per cent very viscous residue
Alpha-methylnaphthalene	*I*	$C_{10}H_7CH_3$	Synthesized from alpha bromonaphthalene, magnesium and dimethylsulphate	Fractionally crystallized to remove impurity (naphthalene)	Conventional high-vacuum still. Sodium in distillation bulb	Distillation bulb at 70 deg C Receiver at −80 deg C	0.01 micron Hg gas pressure	Very small percentage
Tetralin (tetrahydronaphthalene)	*J*	$C_{10}H_{12}$	Eastman Kodak Co., practical grade	Distilled over sodium in low-vacuum still at elevated temperature	Conventional high-vacuum still. Sodium in distillation bulb	Distillation bulb at 40 deg C Receiver at −80 deg C	0.01 micron Hg gas pressure	Very small percentage
Liquid paraffin	*K*	Heavy, white mineral oil	Standard Oil Co. (Indiana)	None	Hickman	Degassing coil at 135 deg C Distilling column at 185 deg C	0.01 micron Hg gas pressure	About 20 per cent of starting material
Commercial cable compound	*L*	....	Cable manufacturer	Degassed and dried by spraying droplets of oil into high vacuum		None of the cable oils were subjected to distillation		
Oil number 107	*M*	Highly refined paraffin	Oils 107 to 113 supplied by Doctor Whitehead, The Johns Hopkins University					
Oil number 109	*N*	Highly refined naphthene						
Oil number 111	*O*	Paraffin blend						
Oil number 113	*P*	Refined naphthene						

highly evacuated sample containers provided with thin glass windows, which could be broken at the proper time by means of a glass-enclosed iron hammer, operated by a magnet (see *X*, figure 2).

Electrical Characteristics

Power Factor

During the preliminary tests on a liquid paraffin and a cable compound, using cell 1, it was found that the power factor of the test samples increased considerably due to bombardment under corona discharge. This can be seen from figures 3 and 4, which show power factor-temperature characteristics of the oils before bombardment and after each of two $6^1/_2$-hour bombardment periods. In all of the preliminary tests, the samples were simply dried and degassed before test and were forced into an evacuated cell of the type shown in figure 1 by means of dry-nitrogen pressure. The nitrogen was removed before the start of the bombardment, which was carried out at a gas pressure of less than one millimeter of mercury. Nitrogen was not used in any of the other tests conducted with cell 1 or cell 2.

It was found that by distilling the bombarded liquid paraffin, a distillate is obtained, the power factor of which is of nearly the same value as that of the sample before bombardment. The constituents of the bombarded sample which are responsible for its high power factor remain in the residue. In these particular tests, distillation was carried out at a temperature of about 180 degrees centigrade in a high-vacuum still suggested by Hickman.[10] In another group of tests, the liquid paraffin was distilled in this manner before bombardment. A purer sample was thus obtained and it

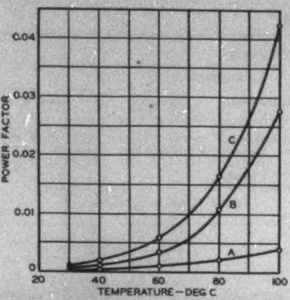


Figure 3. Power factor-temperature characteristics of liquid paraffin. Average of three tests conducted with cell 1

A—Before bombardment
B—After 6½ hours of bombardment
C—After 13 hours of bombardment

was found that the removal of the less volatile fraction and, possibly, of impurities resulted in lower initial power factor values and in a smaller magnitude of changes due to bombardment, but did not result in an elimination of these changes. The power factor-temperature characteristics of one of these samples at various stages of the test are shown in figure 5. In this test, an entirely closed glass system was used in order to prevent any possibility of contamination of the distilled liquid paraffin sample, and the sample was bombarded, the bombarded oil was distilled, and the distillate was rebombarded without opening the system. An automatic Sprengel pump, included in the system, served to store a part of the evolved gas in a gas-collecting bottle for subsequent analysis and also to recirculate the remainder of the gas through the oil in the bombardment chamber in order to support the movement of the oil from this part of the cell to the measuring chamber.

At the time when these studies were started, there was a widespread belief that, since most pure hydrocarbons were known to have excellent electrical characteristics, bombardment of a hydrocarbon sample would not result in changes of its electrical characteristics unless the bombardment occurred in the presence of oxygen or some other impurity. The test reported here showed, however, that despite the most rigid exclusion of contaminants, increases of power factor were obtained due to bombardment and that material of higher boiling point which was produced by the bombardment was responsible for this change. Since it could be concluded that the larger molecules formed in the discharge, by condensation or polymerization or both, were hydrocarbons which exerted a harmful effect on the power factor of the sample and since the structure of these larger molecules should depend on the structure of the starting material, a study of the effect of the molecular structure of a hydrocarbon on the power factor change due to bombardment was undertaken.

Cell 2, which was designed for this study, was first tried on samples of distilled liquid paraffin. In these tests as well as in all others conducted with cell 2, the gas pressure in the cell at the start of the bombardment period was a small fraction of one micron of mercury. Results obtained in one-hour and four-hour bombardment periods are shown in figure 6. It is apparent from a comparison of these results with those given in figure 5 that this cell is capable of producing results considerably faster than the cell shown in figure 1. Ten hydrocarbons of known type structure were studied with this cell, and the results of determinations of power factor-temperature characteristics are shown graphically in parts *A* to *J* of figure 7, each part depicting characteristics of the individual hydrocarbon obtaining before and after four hours of bombardment. Since the power factor values cover a range from 0.0001 to almost 1.0, a four-cycle logarith-

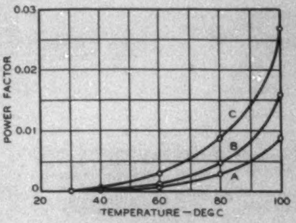


Figure 4. Power factor-temperature characteristics of a cable compound. Average of three tests conducted with cell 1

A—Before bombardment
B—After 6½ hours of bombardment
C—After 13 hours of bombardment

Table III. Conductivities of Various Compounds at Several Temperatures Before and After Bombardment

Compound	Conductivity*	Before Bombardment						After Bombardment					
		100°C	80°C	60°C	50°C	40°C	25°C	100°C	80°C	60°C	50°C	40°C	25°C
Hexadecane	A-C		0.066	0.033		0.013			5.04	3.40		1.78	
	D-C		0.0002	0.0001		0.0001			0.859	0.335		0.120	
	A-C/D-C		330	330		130			5.87	10.1		14.8	
Decalin	A-C				0.162	0.142	0.107			8.98	9.63	5.46	4.89
	D-C				0.0003	0.0002	0.0001			0.062	0.048	0.029	0.017
	A-C/D-C				540	710	1070			144.8	200.5	188.2	287.6
Turpentine polymer	A-C	1.29	0.43	0.11		0.030		4.44	1.93	1.48		0.19	
	D-C	0.884	0.36	0.072		0.017		2.39	0.684	0.166		0.031	
	A-C/D-C	1.46	1.29	1.53		1.76		1.86	2.82	8.91		6.14	
Alpha-methylnaphthalene	A-C			2.23	1.71	1.26	0.666			212.3	115.0	66.4	31.3
	D-C			0.124	0.097	0.066	0.033			44.2	21.9	12.4	4.57
	A-C/D-C			18.0	17.6	19.1	20.2			4.80	5.25	5.37	6.85
Number 107	A-C	0.344	0.123	0.054		0.016		8.44	3.13	0.772		0.133	
	D-C	0.066	0.025	0.008		0.004		0.624	0.177	0.062		0.023	
	A-C/D-C	5.22	4.92	6.75		4.00		13.5	17.7	12.5		5.78	
Number 109	A-C	0.526	0.161	0.074		0.030		4.29	1.71	0.460		0.090	
	D-C	0.449	0.096	0.036		0.013		0.503	0.127	0.037		0.010	
	A-C/D-C	1.17	1.68	2.05		2.31		8.53	13.5	12.4		9.00	
Number 111	A-C	4.38	2.41	1.04		0.365		5.19	2.52	0.960		0.255	
	D-C	0.216	0.068	0.023		0.006		0.211	0.065	0.026		0.008	
	A-C/D-C	20.3	35.4	45.2		60.8		24.6	38.8	36.9		31.9	
Number 113	A-C	3.22	1.58	0.664		0.219		8.96	4.69	1.97		0.674	
	D-C	1.42	0.784	0.377		0.135		0.462	0.129	0.042		0.017	
	A-C/D-C	2.28	2.02	1.76		1.62		19.4	36.4	47.0		39.7	

* Conductivities given in mhos × 10^{13}. A-c conductivity calculated from 60-cycle power factor values. D-c conductivity is one-minute conductivity.

mic scale was used in order to enable easy comparison of all ten compounds. These characteristics represent average values from two or more test runs except in the case of tetralin (*J*) in which only one test run is represented. This material, tetralin, attacked the glass of the bombardment chamber during bombardment, chipping out small pieces from the glass wall. Similar experiences with tetralin were reported by Becker.[8] The initial power factors of a few of the compounds, namely, turpentine polymer (*H*), alpha-methylnaphthalene (*I*), and tetralin (*J*), were higher than was expected. It should be pointed out, however, that it is very difficult to obtain these hydrocarbons in a very pure state. The increases in power factor were quite different for the various types of hydrocarbons. It will be noted that very large increases were obtained for the straight chain hydrocarbons, hexadecane (*A*) and hexadecene (*B*), for the saturated cyclic hydrocarbon, decalin (*G*), for the aromatic hydrocarbon, alpha-methylnaphthalene (*I*), and for the cyclic aromatic-aliphatic hydrocarbon, tetralin (*J*). The smallest power factor increases were obtained for saturated and unsaturated branched chain hydrocarbons, oils number 4555*a* (*D*), number 4530 (*E*), and number 4555 (*F*), and for the unsaturated cyclic hydrocarbon, turpentine polymer (*H*). The power factor increase for the hydrogenated oil number 4530*a* (*C*) was quite large, however. Considering both the initial power factor values and the increase of power factor values with bombardment, it is found that certain members of the branched chain hydrocarbons gave the best results. This statement is modified, however, in a later section of this paper under "Discussion." In addition to the oils of known type molecular structure, four oils representative of those offered to the cable trade were tested; for the latter, practically no information is available regarding their origins, refinement, or molecular structure. These four oils were chosen from a number of oils kindly supplied by Doctor Whitehead, who used them in other investigations.[11,12] The oils tested were selected to include some of high as well as some of low viscosity, and also to represent paraffin-base and naphthene-base types. The power factor-temperature characteristics of these oils before and after bombardment are shown in figure 8. It will be noticed that three of the four samples suffered quite a power factor increase due to bombardment. The fourth sample, oil number 111 (*O*), a low-viscosity paraffin-base product showed a very small change.

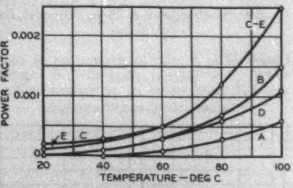


Figure 5. Power factor-temperature characteristics of liquid paraffin distilled before test. Test conducted with cell 1 in entirely closed glass system

A—Before bombardment
B—After 13 hours of bombardment
C—After 39 hours of bombardment
D—Distillate from *C*
E—Bombarded distillate (13 hours)

Conductivity

In a number of test runs, determinations were made of one-minute d-c conductivity to learn how this characteristic of the oil was affected by corona discharge. Also, equivalent a-c conductivities were calculated from the power-factor values to enable comparison between a-c and d-c conductivites. A number of typical results are listed in table III.

It will be noted that in the case of the four hydrocarbons of known type molecular structure there were very large increases in d-c conductivity due to bombardment, whereas in the case of the cable compounds, changes were slight except for oil number 107 (*M*). The ratios of 60-cycle a-c conductivity to one-minute d-c conductivity cover a wide range for the first group and a much smaller range for the second group.

A few special test runs were conducted in which the changes in d-c and a-c conductivity as a function of time of direct-voltage application were studied. In one particular test, the sample consisted of the residue from bombarded decalin redispersed in the distillate, which had been distilled from the bombarded decalin earlier in the studies. The measurements were made at 50 degrees centigrade and approximately 20 volts per mil. First, a number of power factor measurements were made without intervening d-c measurements, then direct voltage was applied for one-half hour, and after this, power factor values were again measured at 15-minute intervals for some time without intervening d-c measurements. The results were used in plotting the curves of figure 9. During the one-half-hour d-c application, the d-c conductivity decreased quite rapidly at first and then more slowly; the power factor dropped from 0.1243 to 0.0380, and upon discontinuation of the direct voltage increased again at a rapidly diminishing rate. Similar observations, but involving much smaller changes, have been made by Whitehead and Shevki[13] on unbombarded cable impregnants.

Bombardment Current

In these studies an attempt was made to have test conditions closely parallel those encountered in commercial service. For this reason the bombardment voltage, rather than the current, was maintained constant; and measurements of the current involved in the discharge were made by means of a vacuum-thermocouple microammeter connected in the high-voltage circuit. Considerable difficulty was experienced in these measurements, particularly when the range of the meter had to be increased by means of external multipliers, because of the high-frequency components in the discharge current. An all-wave radio receiver, covering a

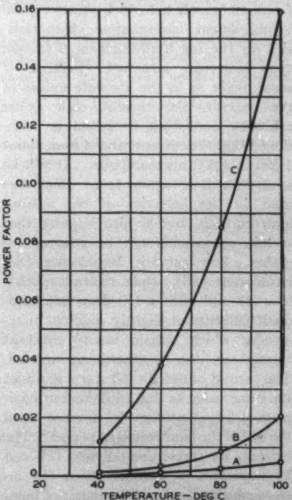


Figure 6. Power factor-temperature characteristics of liquid paraffin distilled before test. Tests conducted with cell 2

A—Before bombardment (average of seven tests)

B—After one hour of bombardment (average of four tests)

C—After four hours of bombardment (average of three tests)

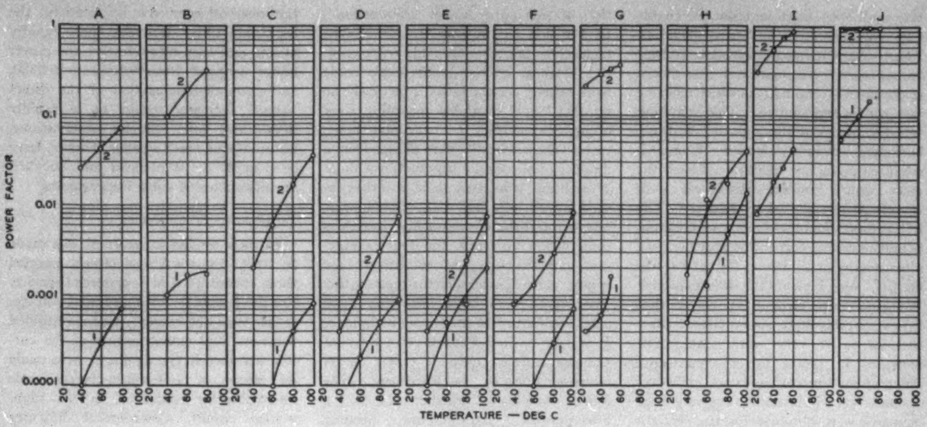


Figure 7 (above). Power factor-temperature characteristics of ten hydrocarbons of known type molecular structure

1—Before bombardment

2—After bombardment at 15 kv, 60 cycles, for four hours

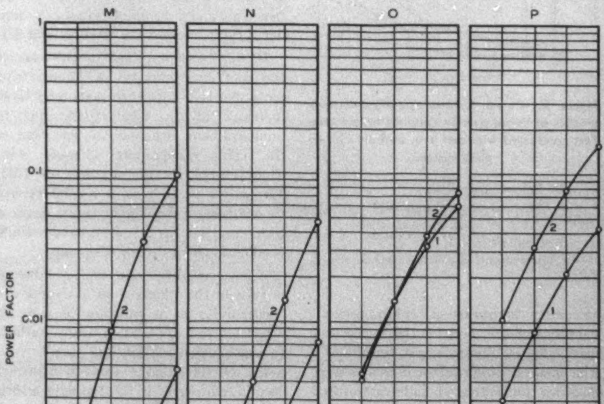
Letters *A* to *J* refer to designation of compounds (table II)

Figure 8 (below). Power factor-temperature characteristics of four cable compounds

1—Before bombardment

2—After bombardment at 15 kv, 60 cycles, for four hours

Letters *M* to *P* refer to designation of compounds (table II)



range from 550 kilocycles to 61 megacycles, indicated frequencies up to 40 megacycles to be present in the discharge.

In order to show the type of results obtained by the current measurements, figure 10 is included which shows typical bombardment current-time characteristics for the ten hydrocarbons of known type molecular structure. Because of some doubt as to the absolute values of the current, the current scale is in arbitrary units, but it should be mentioned that the current ranged from about 1,000 to 4,600 microamperes. It will be seen that here again large differences exist in the behavior of the various hydrocarbons, but it also appears that certain compounds can be grouped together. For instance, hexadecane (*A*), hexadecene (*B*), alpha-methylnaphthalene (*I*), and tetralin (*J*) draw bombardment currents of slightly different magnitudes which remain nearly constant throughout the bombardment period. The current of decalin (*G*) starts at about the same value as that of these four compounds but continues to increase until the end of the bombardment period. The currents for turpentine polymer (*H*) and hydrogenated oil number 4555*a* (*D*) increase during the first 30 minutes of bombardment, then decrease to the end of the bombardment period; the current for the unsaturated oil number 4555 (*F*) is somewhat similar. Bombardment currents of the oil number 4530 (*E*) (unsaturated) and of the hydrogenated oil number 4530*a* (*C*) increase rapidly during the first few minutes, remain at the maximum for a short time, and then decrease. When the unsaturated oil number 4530 (*E*) was bombarded, it was found that during part of the bombardment period, the current was larger than the range of the microammeter and multiplier (2,500 microamperes). During tests on the hydrogenated oil number 4530*a* (*C*) another multiplier was used, approximately doubling the previous range; the values measured under this condition were not directly comparable with those measured on the other nine compounds since the exact multiplication factor of the multiplier was not known because of the error due to high frequencies.

The bombardment currents encountered in studying the commercial cable compounds numbers 109 (*N*), 111 (*O*), and 113 (*P*) were similar to those of the group of compounds including (*A*), (*B*), (*I*), and (*J*) of figure 10. The current of compound number 107 (*M*) was also of the same magnitude as the above group of compounds during the first 30 to 45 minutes of the bombardment period; after this the current was larger than the range of the microammeter and remained so until the end of the period.

Dielectric Constant and Dielectric Strength

The dielectric constants of the oil samples at various temperatures before and after bombardment were obtained for a large number of the samples tested. There was practically no difference in the first three significant figures of the corresponding values of the dielectric constants before and after bombardment. These values were calculated from capacity determinations which were incidental to the power-factor measurements in the case of the cell containing oil, and which were obtained for the empty cell by means of a capacity bridge. The dielectric strength of a number of oil samples bombarded in cell 1 was determined before and after bombardment, using test cups described in the ASTM Standard Method D117–36. In practically all cases, the dielectric strength of a sample after bombardment was lower than that before. For instance, the average dielectric strength of samples from three test runs was 44.5 kv before and 30.5 kv after bombardment for the liquid paraffin, and 33.3 kv and 27.1 kv, respectively, for a commercial cable compound.

Other Characteristics

Gas Evolution and Gas Composition

The evolution of gas from an oil under corona discharge is of considerable importance in cable practice. Some have held that a large gas evolution would be beneficial because it would tend to increase the gas pressure in cable voids and would eventually bring about pressure conditions under which the discharge could not maintain itself. Others have reasoned that the gas evolution should be a minimum in order to prevent the gas from forming paths between existing voids and thereby hastening eventual breakdown. Whatever the particular requirements, it was considered important to know the gas evolution of various types of oils and the composition of the gases evolved.

The amounts of gas evolved from ten hydrocarbons of known type molecular structure and from four commercial cable compounds are shown graphically in figure 11. It is evident that the aromatic compound and unsaturated compounds of other types of molecular structure gave off smaller amounts of gas than did the saturated compounds. It is also evident that of the four cable compounds, those of paraffinic base gave off more gas than did those of naphthenic base, and that the more highly refined oils gave off more gas than did the less refined oils. In

Figure 9. Effect of one-half-hour direct-voltage application on power factor and conductivity of bombarded decalin

Measurements:
Temperature, 50 degrees centigrade
Alternating voltage, 200 volts, 60 cycles
Direct voltage, 180 volts
Electrode spacing, 0.010 inch

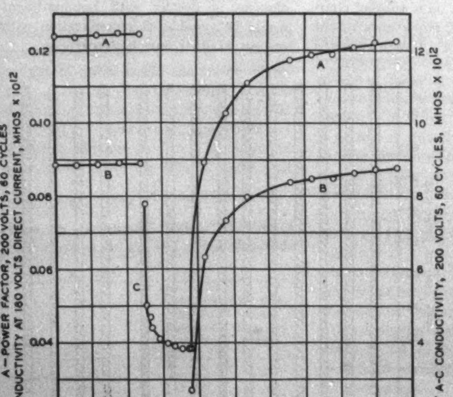
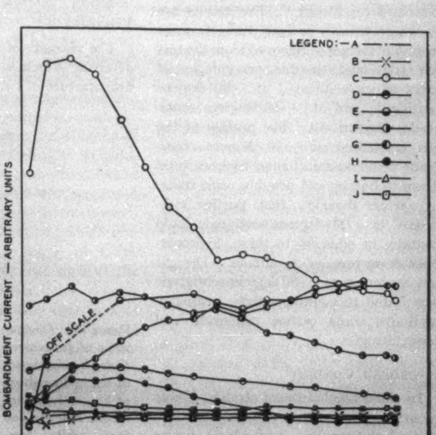


Figure 10. Bombardment-current versus time-of-bombardment characteristics of ten hydrocarbons of known type molecular structure

Letters *A* to *J* refer to designation of compounds (table II)



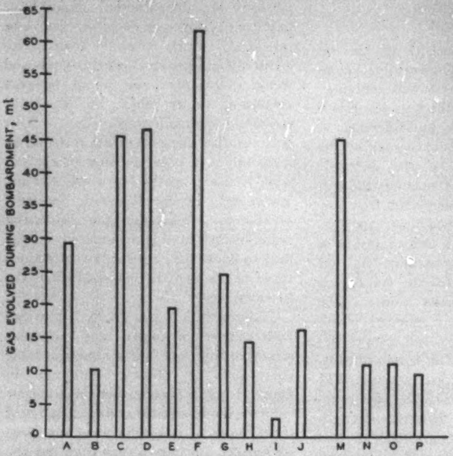


Figure 11. Gas evolved during bombardment of ten hydrocarbons of known type molecular structure and four cable compounds

Bombardment of four hours at 15 kv, 60 cycles. Letters refer to designation of compounds (table II)

this connection, it should be mentioned that the degree of refining is also an indication of the degree of saturation, since the refining process tends to eliminate unsaturates. Similar results were obtained by Schoepfle and Connell[7] and by Schoepfle and Fellows[14] by using cathode-ray bombardment, and more recently by Nederbragt[15] and by Berberich[16] by means of corona discharge.

The compositions of the evolved gases were determined by means of a method described by Fleiger.[17] The results are shown graphically in figure 12. It can be seen that the gas as removed from the test cell contained sizeable percentages of gases which condensed at −80 degrees centigrade and at −180 degrees centigrade, respectively. The portion of the gas condensed at −80 degrees centigrade could contain lighter hydrocarbons down to butane and possibly some traces of carbon dioxide; that portion condensed at −180 degrees centigrade could contain, in addition to these, hydrocarbons from propane to ethane. The gas not condensed at −180 degrees centigrade was found to contain mainly hydrogen, methane, some carbon monoxide and some nitrogen.

Hydrophil Content

In these bombardment studies, it was of utmost importance to prevent oxidation of the samples, particularly during the bombardment period. In order to detect whether air had leaked into the cell during a bombardment period, the total oxidation products in a sample before and after bombardment were determined in practically all test runs. The hydrophil test as described by Wyatt, Spring, and Fellows[18] was used for this purpose. Results of hydrophil determinations made during the tests on the ten hydrocarbons of known type molecular structure are given in table IV, and it is evident from the results that there were no significant increases in hydrophil content. It should be pointed out, in fact, that decreases in hydrophil content were observed for two of the compounds tested.

Viscosity

The viscosity of an oil is another characteristic which is of importance in the manufacture of cables. It was expected that this characteristic would be affected by corona discharge and measurements of viscosity were made in the case of a few representative compounds. The results are shown in parts *A* to *J* of figure 13; the two curves of each part represent viscosity-temperature characteristics before and after bombardment. It is quite evident that there are three groups of compounds with respect to the magnitude of the viscosities. In the lowest viscosity group are hexadecane (*A*), hexadecene (*B*), decalin (*G*), alpha-methylnaphthalene (*I*), and tetralin (*J*). In the medium viscosity group are the unsaturated and the hydrogenated oils number 4530 (*E*) and number 4530*a* (*C*), and also the turpentine polymer (*H*). In the highest viscosity group are the unsaturated and the hydrogenated oils number 4555 (*F*) and number 4555*a* (*D*). It is of interest to note that despite these differences in viscosity, nearly all compounds suffered a substantial increase in viscosity when subjected to corona discharge. The only exceptions were hexadecane (*A*) and decalin (*G*). Increases in viscosity were also obtained in the tests in which cable compounds were used.

Miscellaneous

A number of determinations other than those already mentioned were made on some of the compounds, particularly on decalin. This compound was singled out because it was particularly suitable for certain tests, and because it was expected that most of the findings regarding changes in decalin with bombardment would be capable of generalization with respect to other pure hydrocarbons.

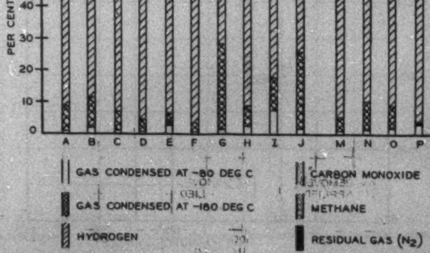


Figure 12. Composition of gas evolved during bombardment of ten hydrocarbons of known type molecular structure and four cable compounds

Bombardment of four hours at 15 kv, 60 cycles. Letters refer to designation of compounds (table II)

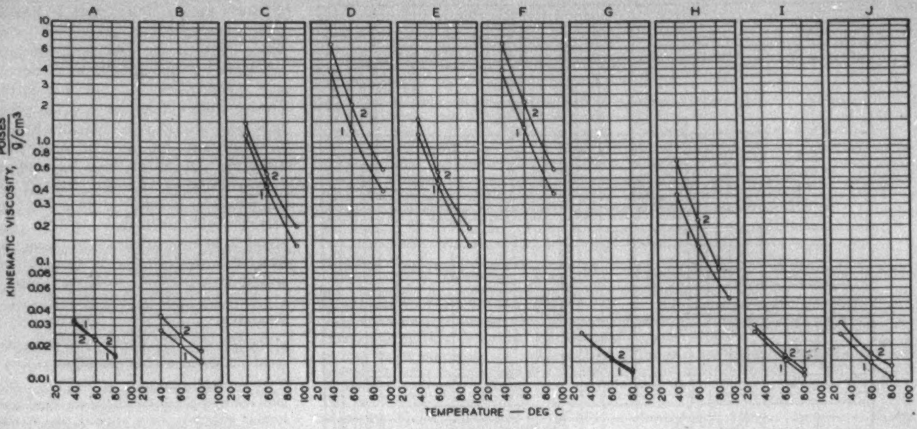


Figure 13. Viscosity-temperature characteristics of ten hydrocarbons of known type molecular structure

1—Before bombardment
2—After bombardment at 15 kv, 60 cycles, for four hours
Letters *A* to *J* refer to designation of compounds (table II)

Iodine-number determinations were made in order to investigate changes in the degree of saturation due to corona discharge. It was found that the iodine number of decalin increased considerably with bombardment. In the preliminary tests of the studies conducted with cell 1 on a cable compound and on pure liquid paraffin, it was observed that the iodine and sulphuric-acid tests indicated an increase in the content of unsaturated components as a result of corona discharge.

Since it was found that the bombarded hydrocarbons contained small amounts of compounds of high boiling points, and since the viscosity of the samples increased due to corona discharge, attempts were made to determine the molecular weight of these larger molecular aggregates. In the case of decalin, vacuum distillation at room temperature and at 100 degrees centigrade, and selective solvation were resorted to. It was found that nearly all of the sample distilled at room temperature in a good vacuum; this material was composed primarily of decalin (molecular weight 138), but also contained some unsaturated products. The part of the residue which distilled at 100 degrees centigrade had an average molecular weight of 198. The material remaining after this distillation was a viscous amber oil of an average molecular weight of 429. It is probable, however, that this residue consisted of a series of polymers of different molecular weights. A portion of this residue was dissolved in benzene and precipitated with isopropyl alcohol. After several such treatments, a white powder was obtained which had an average molecular weight of 1,600. Although it is probable that some of the residue is of a still higher order of polymerization, it is noteworthy that most of the polymerized product which is formed from decalin by bombardment and which seems to be responsible for the increase in power factor of decalin with bombardment is of so relatively low an order of polymerization.

Table IV. Hydrophil Values of Various Hydrocarbons Before and After Bombardment

	Per Cent Hydrophils	
	Before Bombardment	After Bombardment
Hexadecane (*A*)	0.006	0.031
Hexadecene (*B*)	0.033	0.20
4530 (hydrogenated) (*C*)	2.0	0.96
4555 (hydrogenated) (*D*)	0.005	0.021
4530 (*E*)	3.9	1.9
4555 (*F*)	0.11	0.14
Decalin (*G*)	0.002	0.025
Turpentine polymer (*H*)	0.16	0.17
Alpha-methylnaphthalene (*I*)	0.000	0.036
Tetralin (*J*)	0.019	0.026
Liquid paraffin (*K*)	0.007	0.15

DISCUSSION

Some of the characteristics of the oil samples which have been investigated are closely interrelated. An example of this is found in the effect of viscosity on the variation of power factor and conductivity of oils at different temperatures, and this effect cannot be ignored when oils of different viscosities are being compared. It is generally recognized that both power factor and conductivity depend not only on the number of ions present, but also on their mobility, which in turn is affected by the viscosity of the sample. In figure 14 are shown power factor-kinematic viscosity characteristics of a number of samples before and after bombardment. It can be seen that in most cases these characteristics are nearly straight lines. With very few exceptions, the slope (power factor to viscosity) of these lines is in the neighborhood of -1, indicating that the power factor values are nearly inversely proportional to the kinematic viscosity; that is, the change in power factor with temperature can be practically accounted for by the corresponding change in viscosity.

Having thus added to the power factor-temperature characteristics the more fundamental relation of power factor versus viscosity, a better criterion is available for comparing various oils with regard to their ability to withstand corona bombardment as judged by power factor change. It can now be seen that a group of six oils, namely, hydrogenated oil number 4530*a* (C_1), liquid paraffin (K_1), oil number 4530 (E_1), oil number 4555 (F_1), turpentine polymer (H_1), and the hydrogenated oil number 4555*a* (D_1) rate nearly the same before bombardment. After bombardment, however, the turpentine polymer (H_2) and the oil number 4530 (E_2) are considerably better than the remaining four oils of the group mentioned. Similar attempts

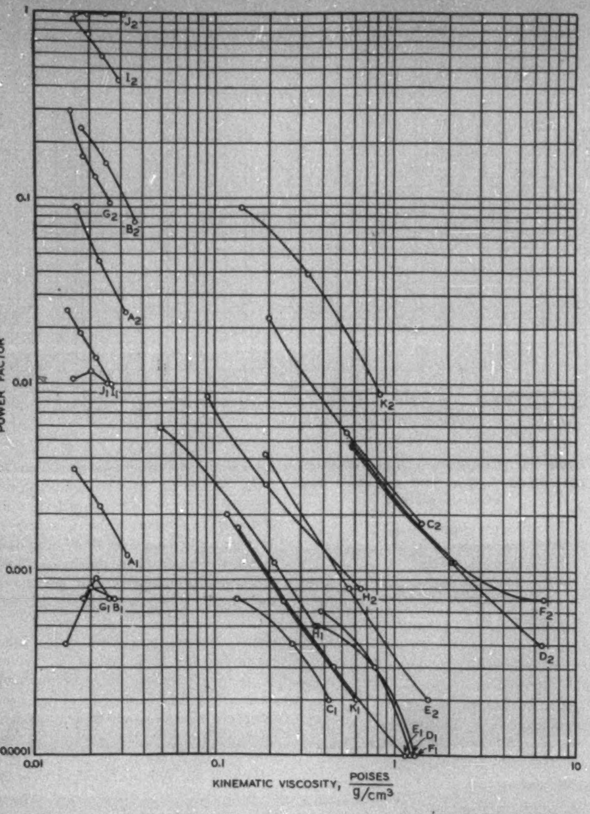


Figure 14. Power factor-viscosity characteristics of liquid paraffin and ten hydrocarbons of known type molecular structure

1—Before bombardment
2—After bombardment at 15 kv, 60 cycles, for four hours
Letters *A* to *K* refer to designation of compounds (table II)

to compare properties of various oils independent of the temperature were discussed in a paper by Whitehead[19] in which he suggested the use of the product of viscosity and conductivity as a measure of the purity of an oil, since this product can be considered a measure of the free ions present.

It can be assumed that viscosity in connection with surface tension has a decided influence on the bombardment current and the gas evolution of an oil under corona discharge, by affecting the size and number of gas bubbles in the oil in which the bombardment takes place. It is also recognized that the molecular structure of the hydrocarbon has a considerable influence on the amount of gas evolved. Discussing the generation and absorption of gas in insulating oils under the influence of an electric discharge, Nederbragt[15] suggested the addition of ten per cent or less of aromatics to cable oils in order to decrease their gas-producing tendency. In view of the results of the present studies it appears important, however, to ascertain to what extent this addition affects the other characteristics of the oil in relation to corona discharge. It would be of importance, for instance, to know the effect of this admixture on the power factor change of the oil with bombardment.

Under the influence of corona discharge, a great number of reactions take place in a hydrocarbon oil, the reaction products ranging from gases to liquids and solids. Similar observations were made by Lind and Glockler,[20] Harkins and Gans,[21] Austin and Black,[22] Sommerman,[23] and others. It appears from the present studies that some reaction products are changing continually during bombardment and even for some time after the sample has been exposed to corona discharge, depending largely on the molecular structure of the oils. This fact, probably more than anything else, seems to be responsible for an occasional lack of reproducibility of results observed in these corona-discharge studies.

SUMMARY

1. A test cell suitable for use in bombardment studies on oils was developed.

2. Pure liquid paraffin, various cable oils, and ten hydrocarbons of known type molecular structure were studied, and it was found that a number of their characteristics are changed by corona discharge.

3. The power factor of all samples increased with bombardment.

4. The one-minute d-c conductivity of bombarded samples was in most instances considerably lower than the a-c conductivity calculated from power-factor values.

5. Application of d-c potential to bombarded decalin for extended periods showed that the power factor and conductivity of the samples were thereby decreased considerably, the improvement being maintained only during and shortly after application of the potential.

6. The material responsible for the changes in power factor and conductivity, and produced during the bombardment, constitutes an extremely small portion of the bombarded oil. It consists of material which remains as residue during distillation of the bombarded oils at the temperatures and pressures used in these studies.

7. Currents resulting from application of identical a-c bombardment voltages to the cell were widely different for the various oils.

8. The gas evolution of the various oils under bombardment was widely different, generally more gas being obtained from the saturated than from the unsaturated compounds.

9. In practically all cases an increase in viscosity resulted from the bombardment of the oils.

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21. A Spectroscopic Study of the Decomposition and Synthesis of Organic Compounds, W. D. Harkins and D. M. Gans. *Journal* American Chemical Society, volume 52, 1930, page 5165.

22. The Chemical Behavior of Some Benzoid Hydrocarbons in the Tesla Discharge, J. B. Austin and J. A. Black. *Journal* American Chemical Society, volume 52, 1930, page 4552.

23. Properties of Saturants for Paper-Insulated Cables, G. M. L. Sommerman. Electrical Engineering, May 1937, page 566.

Discussion

L. J. Berberich (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): As the authors have pointed out, cable engineers have recognized for some 20 years that corona discharge in cable voids affects oil-impregnated paper insulation. However, except for the formation of a waxy product which came to be known as "*X* wax" or "cable cheese," the nature of the reaction was not at all understood for a considerable length of time. It remained for the chemists, and logically so because this is largely a chemical problem, to throw important light on the behavior of hydrocarbons when subjected to gaseous electric discharge. The paper by Schoepfle and Connell published in 1929 (reference 7 of the paper) was the first, I believe, to show conclusively that the saturated highly refined petroleum oils are more strongly affected by cathode rays as well as corona discharge than the lightly refined, unsaturated oils. This has been of great practical significance and was in general agreement with the results of an investigation on a series of pure hydrocarbons given in a companion paper (Schoepfle and Fellows, *Industrial and Engineering Chemistry*, volume 23, 1931). Apparently these two papers inspired much of the work that followed.

More recently, Nederbragt (reference 15) and I (reference 16), working independently, have found that the addition of aromatic compounds to cable oils resulted in marked lowering of the gas evolution. Before the present paper appeared, the origin of the increase in power factor and dielectric loss in bombarded oils was completely obscure. The authors have presented excellent evidence that the loss is caused by the high-molecular-weight polymerization products formed. This and the demonstration that these products are charged represent an important addition to our knowledge of this phenomenon.

Most of the investigators of this problem have used the volume of gas evolved as criterion of stability. The authors have used this as well as power factor change. There seems to be only a very approximate relationship between them. An important exception is found in alpha-methylnaphthalene which gave off the least gas yet showed a significant increase in power factor. I have observed in my work in a qualitative way that aromatic compounds, of which alpha-methylnaphthalene is an example, give off little gas, but may produce considerable quantities of high-molecular-weight products. Since the high-molecular-weight products have been shown to be the cause of the power factor increase, perhaps this is the reason why aromatic compounds do not appear to be very stable from the power-factor standpoint. I would appreciate the comments of the authors upon this point and would like to ask if any of the solid products isolated from a bombarded compound were added to an unbombarded oil or compound in order to determine the effect on power factor.

The statement in the paper that viscosity in connection with surface tension influences the gas evolution is in agreement with my experience. The action of the discharge can take place only at the gas-oil interface. Viscosity and surface tension determine the size of the bubbles formed and hence the area of the effective corona. For this reason it is difficult to compare materials of widely different viscosities. The surface-tension variations are usually small. This work perhaps would have been more valuable if compounds and oils of the same viscosity had been chosen. The difficulty in doing this, however, is appreciated.

Charles F. Hill (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): A rather interesting phase of the results reported by Sticher and Thomas is found in table III and involves the ratios of a-c to d-c conductivities as affected by bombardment of oil. High initial ratios decrease appreciably while low ratios increase with bombardment. In most cases the conductivities increased appreciably but one case involves no change in conductivity (number 111 oil) and in the last case of the table for number 113 oil, the d-c conductivity decreased by ten times. It would appear that these data indicate possibilities of investigating the nature of the electric carriers; that is, are they polar or electrolytic, etc. It occurs to me that the d-c carriers might be isolated by electrical conduction through porous membranes.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): This paper refers to the effects of corona discharge such as takes place frequently in solid-type high-voltage cables. The measure of this discharge is known as ionization factor, that is, the increase in power factor in going from a given low stress to a given high stress, the latter being considerably above the operating stresses. In some accelerated aging tests in Chicago on three-conductor 13-kv belted-type cable it was found for some cables that, whereas the ionization factor at room temperature after the cable had been heated to 100 or 115 degrees centigrade was 0.010 or 0.015, the ionization factor after several subsequent heating cycles to a more normal value, that is, 60 degrees centigrade, was less than 0.005 in many cases. In other words, the distribution of compound seemed to change, with the result that there was considerable recuperation.

When it became advisable in this country about 18 years ago to change from rosin-impregnated cables to cables impregnated with lower-loss compounds, in many cases the utilities did not have to wait long to learn the quality of the cable because there were frequent failures. Examination of these failures showed some wax formation and other signs of deterioration in many cases. Since that time the quality of cable insulation has improved very greatly. In the case of cable made, however, between 1926 and 1930 we have found wax formation, and sometimes carbonization, in cable removed from normal service. This cable, however, has had an extremely low rate of failures attributable to the quality of the insulation. The question then arises: What is the life and reliability in service to be for such cable made in the past 12 years where some deterioration has already developed?

It is interesting to note that the so-called cable compound performed outstandingly well in the bombardment tests.

Figure 12 indicates that in some cases five or ten per cent of the gas is carbon monoxide. In view of the precautions taken by the authors to prevent the presence of oxygen in their test apparatus, the presence of carbon monoxide is inexplicable.

F. M. Clark (General Electric Company, Pittsfield, Mass.): The paper by Sticher and Thomas is to be welcomed as demonstrating once more the great dependence of dielectric engineering on the molecular and chemical phenomena. One can no more speak of the dielectric properties of liquid insulation without clearly describing the fundamental chemical characteristics of the liquid under discussion. In this respect it is unfortunate that a clearer description of the cable compounds used in the paper is not given. The reference to Doctor Whitehead's work helps but little for the compounds are not clearly described in the reference. Aside from the viscosity, and the other oil properties usually given, such as flash, fire, and pour points, the oils are merely described as highly refined or refined paraffin, naphthenic, or paraffin blend oil. In view of the loose usage of these terms during the past few years, this terminology yields but little information. Whitehead, however, does clearly define the oils involved as specially prepared for the work described and not identical with the oils used in commercial cable operation. The high pour-point values for the thin low-viscosity cable oils given by Whitehead (oils number 111 and number 113) clearly indicate a fundamental difference between those oils and those generally used commercially.

The work in my own laboratory is in general agreement with the results of the present paper, as are the generally accepted ideas of the art. Bombardment of saturated paraffinic hydrocarbons evolves more gas than the bombardment of the aromatic and unsaturated hydrocarbons. The more volatile constituents of the bombarded material are characterized by better power factor properties than the nonvolatile residue. In most instances with which I am acquainted the effect is chiefly a pyrogenous decomposition. The more volatile components of the bombarded material are the saturated hydrocarbons of good dielectric properties. The less volatile or nonvolatile are the cracked and polymerized residues. Tests with which I am acquainted tend to indicate that the final product of the bombardment, the *X* wax, is of good dielectric properties. It is the intermediate series of products in various stages of polymerization, especially of unsaturation, which contribute to the higher dielectric losses reported by the authors.

It must be remembered that except in a very general sense, there is no one chemical description that applies to the pyrolysis of organic compounds as varying in structure as those of this paper. In a general sense, the pyrolysis products are unsaturated and tend toward a deeper color than that of the parent molecule. This deepening in color normally is associated with changes in the structure of the hydrocarbons present which also are accompanied by higher dielectric loss. The authors do not describe color changes but presumably they were present with an efficient and decomposition-free distillation of the bombarded product, my own experience has been that the color-producing molecules accumulate in the still residue and contribute to its higher dielectric losses as compared to the colorless distillate. I request from the authors a statement as to the color of their bombarded products and ask whether any refining or decolorization treatment was applied to remove these colored products. If so, what effect on the viscosity and dielectric loss was observed by this decolorization or refining treatment?

The relation between viscosity and power factor as described in figure 14 is of interest and doubtless of significance within a single chemical class of pure organic compounds. The danger lies possibly in the effort to extend such an observation to include all classes of hydrocarbons and hydrocarbon derivatives. Such a step must be made with exceedingly great care.

The authors have indicated that the greatest amount of gas comes from the bombardment of saturated hydrocarbons. Whether this is desirable or undesirable may be a debatable question, as pointed out by the authors, but it is true nevertheless that the saturated water-repelling hydrocarbons are in practical experience generally looked upon as being more dangerous or at least more difficult to handle successfully than the cyclic type of hydrocarbon. But the authors show that in general the cyclic type of hydrocarbon tends to give the higher dielectric loss in the bombarded sample. This is only a general observation, however, for from figure 7 it is to be observed that the turpentine polymer gives a power-factor characteristic of the same order as that observed for the hydrocarbons. This again brings out the important fact that is repeatedly observed in chemico-dielectric studies, it is not safe to make broad generalizations at our present state of knowledge. The chemical structure and peculiar chemical properties of individual compounds within the general classification usually are of an importance which cannot be ignored.

It is true as clearly pointed out by the authors that oxidation effects appear to be eliminated from the results of the present studies. However, bombardment effects produce products of a different chemical type from the parent substance. Aromatic and saturated molecules crack under bombardment and produce unsaturated compounds chiefly of the straight carbon chain type. Such compounds are easily susceptible to change in the dielectric field. Among such changes is a marked susceptibility to oxidation. The use of such products in continued commercial service constitutes a hazard which because of their concentration in localized areas may equal the hazard generally associated with the use of an improperly refined mineral oil. The degree of chemical unsaturation produced as a function of the molecular type bombarded and the chemical and dielectric stability of the bombarded products offer a fertile field for further investigation.

The present paper is confined to a study of the behavior of insulating liquids under bombardment. It has always seemed to me that a problem of equal importance is the determination and comparison of the threshold point at which the gassing of insulating liquids under voltage really begins.

I ask whether the authors have made any attempt to determine the resistance of the various liquids to a chemical change under voltage which results in gas evolution leading to the bombardment effects described in the paper.

Hubert H. Race (General Electric Company, Schenectady, N. Y.): First, it seems to me that the authors should be commended for the careful physical and chemical techniques employed in this work.

Second, I should like to point out a physical measurement which can be used to arrange different liquids in order according to their chemical structure. This property is "specific dispersion" and has the great advantage of being a quick and inexpensive measure of chemical structure in terms of differences in the proportion of aromatic ring and saturated compounds in a liquid hydrocarbon. The specific dispersions of five of the pure chemicals measured by Sticher and Thomas are given by Von Fuchs and Anderson (*Industrial and Engineering Chemistry*, volume 29, 1937, page 319). For these materials I have plotted the correlation between rates of gas evolution and specific dispersion as shown in figure 1. In general, liquids with higher specific dispersions show lower rates of gas evolution. Unpublished data on "stamp capacitor" life tests assembled by H. W. Bousman of our general engineering laboratory indicate a similar correlation such that in general, liquids in the same viscosity range having higher specific dispersions show longer life. It is also significant to point out that only one material (*I*) showed a lower rate of gas evolution than did oil (*P*), which is the nearest in structure to the oil which has had widest use in oil-filled cable in this country.

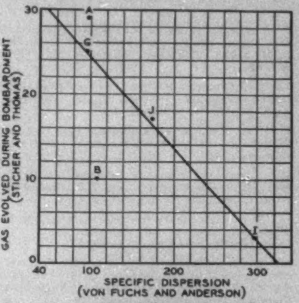

Figure 1. Correlation between specific dispersion and rate of gas evolution under corona bombardment

It is suggested, therefore, that further studies along this line include measurements of "specific dispersion."

Wm. A. Del Mar (Phelps Dodge Copper Products Corporation, Yonkers, N. Y.): Our laboratories have been making tests of oil stability with a modification of the bombardment cell described by G. W. Nederbragt in *Journal* IEE (London) volume 79, 1936, pages 282–90.

The test is made by placing a sample of oil in an evacuated cell and producing, by means of a 60-cycle potential, a glow discharge in the gas remaining over the surface of the oil. The amount of gas evolved, the change in power factor, and the change in resistivity are noted, the stability of the oil being gauged by these three characteristics.

A dimensional drawing of the cell used for this test is shown in figure 2 of this discussion. It consists of a glass cylinder 50 millimeters external diameter and 250 millimeters external length, with hemispherical ends. The thickness of the glass is 1.6 millimeters. It is equipped with external electrodes in the form of tin-foil belts 95 millimeters wide and 28 millimeters apart. A funnel and stopcock provide means for introducing a 20-gram sample of oil. A mercury manometer measures the gas evolution by indicating the change of pressure in the cell. Two such cells are used, in order that each oil may be tested, if desired, in comparison with some other oil.

The electrical circuits are shown in figure 3 which shows two cells, each fed by

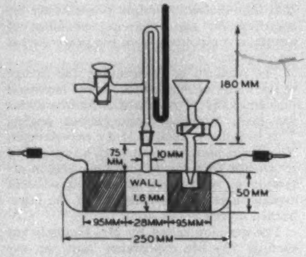

Figure 2. Oil-stability test cell

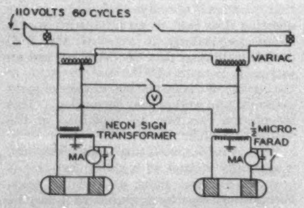

Figure 3. Electrical circuit of oil-stability test set

a 15,000-volt 60-cycle gas-tube sign transformer. A milliammeter is in each cell circuit. An adjustable-ratio autotransformer is used to control the voltage fed to each step-up transformer, so as to enable equal currents to be passed through the two cells.

A diagram of the oil-conditioning equipment is shown in figure 4. Oil is degasified in the cell by dropping slowly into a vacuum of less than 0.1 millimeter mercury from the funnel. The vacuum regulator is then set at an arbitrary value, usually 1 millimeter and the oil left to "condition" overnight at this pressure. Gas, usually CO$_2$, is admitted through an adjustable capillary leak and dried by passing through a P$_2$O$_5$ moisture trap.

The following precautions have been found necessary to insure reproducible results in comparing oils:

1. The cells and their electrical equipment must be identical.

2. Both the volume and surface area of the oil samples in the cells must be identical.

3. The starting vacuum must be the same.

4. Stopcock leakage must be carefully eliminated preferably by the use of a glycerin base lubricant, insoluble in oil.

5. Milliammeters must be checked carefully before each test. The rectifier type of milliammeter does not retain its calibration in this service, due probably to high-frequency transients. Some help is obtained by shunting each ammeter permanently by a 0.5-microfarad capacitor and by employing a short-circuiting switch by means of which the milliammeter may be kept out of circuit except when readings are being taken. Calibration may easily be made by means of a 100,000-ohm series resistor and a known alternating voltage.

We have found that at 1.0 millimeter pressure approximately 12,000 volts are required to produce a current of 0.8 milliampere through the cell. Viscous oils (solid-type cable oils) seem to require about eight per cent lower voltage to maintain this current than the less viscous oils used in oil-filled cable.

The test, carried out with the above precautions, gives results which are reproducible within about plus or minus five per cent. Blanks, that is, without voltage, show that no change of power factor, within the limits of accuracy of the Schering bridge, occurs as the result of transferring the oil between the Nederbragt bombardment cell and the Berberich measuring cell.

The cell used by Sticher and Thomas has the advantage of permitting continuous curves of gas evolution, power factor, and resistivity to be made, whereas the Nederbragt cell is limited to continuous curves of gas evolution and merely "before and after" reading of power factor and resistivity.

Some of the conclusions reached are as follows:

1. This test produces two types of deterioration of oil. One type is evidenced by increase in gas pressure above the specimen, believed to be caused by partial decomposition of the oil. The other type is evidenced by an increase in power factor and decrease in resistivity of the oil. These two types of deterioration do not necessarily go together. On the contrary, if we except blends containing certain grades of wood rosin, it is usual for oils having the better gassing characteristics to, have inferior power factor and resistivity characteristics, and vice versa. Highly refined water-white oil was poor by both criteria.

2. Oils of high viscosity (solid-type cable oils), in general, showed greatest deterioration by gassing. Oils of low viscosity (oil-filled-cable oils) produced less gas but showed greater power factor and resistivity changes.

3. We confirm Nederbragt's results on the value of added aromatics in reducing gas evolution, but find the practical application difficult.

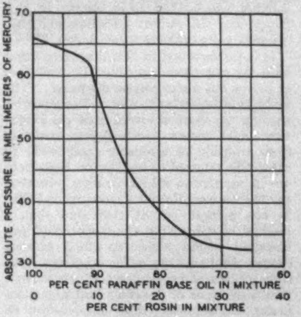

Figure 5. Oil-stability tests-gassing under glow discharge

Run of 1,400 minutes

Temperature = 30 degrees centigrade

Initial pressure = 1.0 millimeter of carbon dioxide

Sixty-cycle current = 0.80 milliampere

4. The substitution of CO$_2$ for air as the medium in the discharge cell has little or no effect on the results.

5. Viscous oils as used in the solid-type cables are intermediate in gassing between water-white oil and oil-filled-cable oil.

6. Power factor increases occur without increase of hydrophil number.

7. There is little difference in gassing stability between rosin-free paraffin base and rosin-free naphthene base oils, as used in solid-type cables.

8. Wood rosin added to paraffin base oil adds greatly to the gassing stability, as shown in figure 5 of this discussion.

9. The effect of wood rosin on power factor stability is less easy to evaluate because there are four effects to consider, as follows:

(*a*). Effect of wood rosin on magnitude of power factor.

(*b*). Effect of wood rosin on power-factor temperature relation.

(*c*). Effect of wood rosin on each of above after bombardment in the Nederbragt cell.

(*d*). Effect of degree of type or purity of wood rosin on each of above three.

It is impossible in the space of this discussion to report each of these four items, except in the briefest way.

In general, wood rosin increases oil power factor, but whereas in some grades the effect is very great, in others it is almost negligible.

Some grades of rosin increase and some decrease the rise of power factor with temperature.

Some grades of rosin increase and some decrease the effect of bombardment on power factor.

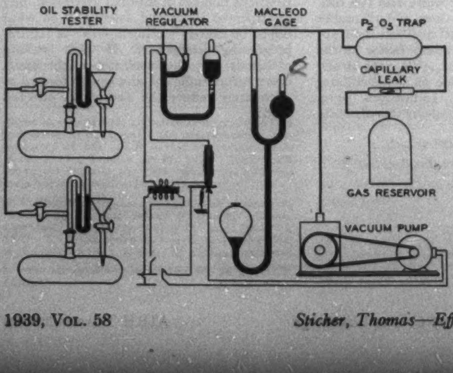

Figure 4. Vacuum system of oil-stability test set

The test has been exceedingly useful in enabling improved grades of rosin to be selected.

We hope to be able to give more specific details of the various rosins at some later date. Acknowledgments are due to J. H. Palmer and E. T. Merrell for their assistance in the preparation of this material.

Joseph Sticher and D. E. F. Thomas: The authors are grateful to the discussers for the interest which they have shown in this paper, and the various questions and suggestions are genuinely appreciated.

It is perhaps best in this closure to begin with the questions regarding the evolution of gas by oils under corona discharge. The findings of Nederbragt and of Berberich regarding the marked lowering of gas evolution under corona bombardment resulting from addition of aromatic compounds to cable oils, referred to by Doctor Berberich, are in support of similar findings reported by The Detroit Edison Company in 1929.[1] It was pointed out at that time that a method of controlling the quantity of gas liberated within cables in which gaseous electric discharge can occur suggested itself from results of experiments which showed that a mixture of paraffins and aromatics under bombardment does not liberate as much gas as would be released by the paraffins alone.

Regarding the relationship between power factor increase and gas evolution of oils under corona bombardment which was touched upon by Doctor Berberich, it can be stated that a review of the information available in our files did not reveal such a relationship. This statement is essentially in agreement with the conclusion drawn by Doctor Berberich.

The question by Mr. Halperin regarding the presence, in some cases, of five or ten per cent of carbon monoxide in the gas obtained from bombardment, as shown by figure 12, is very much appreciated since it provides an opportunity to include here a bit of information which might well have been given in the paper. It will be noted, by referring to figure 11, that in all cases in which the reported percentage of carbon monoxide was large, the total amounts of gases evolved were relatively small.

It should be explained that there is a possibility that the extremely small amount of gas reported to be carbon monoxide may have been largely hydrogen which was not removed by the palladium tube diffusion method used to determine the amount of hydrogen in the gas sample. In the gas analysis method used in these tests and described fully in reference 17 of the paper, the gas which is not removed by the palladium tube is subsequently passed into a quartz tube containing cupric oxide at 250 degrees centigrade. This step in the procedure determines the amount of carbon monoxide in the gas sample. It is apparent that any traces of hydrogen not removed by the palladium tube will be burned in the cupric-oxide tube at 250 degrees centigrade and will be reported as carbon monoxide. It will be appreciated that in analyses of very small gas samples a considerable percentage error is usually encountered.

The correlation between specific dispersion and rate of gas evolution under corona bombardment which is shown in figure 1 of the discussion by Doctor Race is extremely interesting. It would seem that, if this correlation could be substantiated by a great number of results from bombardment tests on pure hydrocarbons, such a relation should prove very helpful in the selection of oils for use in the manufacture of oil-impregnated paper-insulated cables.

The tests of oil stability which Mr. Del Mar reported are of considerable interest, particularly those in which the effects of rosin, added to oils, are discussed. With regard to bombarded oils, we have found that they exhibit an increased affinity for oxygen, and for this reason, as well as to prevent other possibilities of contamination, we considered it important in our tests to transfer test samples from the bombardment chamber to the power-factor cell, and vice versa, under vacuum. As a further precaution against possible contamination we refrained from the use of a mercury manometer on the bombardment chamber.

A number of the questions raised in the discussion were concerned with the material of higher molecular weight formed under corona discharge of oils and with the nature of the increased dielectric loss. A considerable amount of experimental work on this phase of the problem has been conducted by The Detroit Edison Company. The inclusion of the results of that work was considered as being beyond the scope of the present paper; these results were therefore scheduled to be the subject of a separate paper in the near future. The questions which have been raised, however, can best be answered as follows.

In a number of cases, bombarded oils were distilled in order to concentrate the polymerized materials. In answer to Doctor Clark's question regarding color changes, it can be stated that in the cases in which water-white oils had been bombarded, the bombarded oils exhibited a more or less yellow tinge. Upon distillation, the distillate was again water white and the residue exhibited in some cases a dark amber color. In all cases, the distillate had approximately the same power factor as the oil before bombardment. Viscosity determinations were not made on the distillates from bombarded oils. Indications were, however, that in other respects this distillate was closely the same as the material before test, and it can be expected that this is also true for the viscosity.

The solid products (white powder) isolated from a bombarded compound, which Doctor Berberich inquired about, were added to unbombarded compound of the same kind from which the solid material was obtained. It was found that a very pronounced increase of power factor values resulted from this addition. While tests of this nature were not made on aromatic compounds, there seems to be good reason to concur in Doctor Berberich's suspicion that high-molecular-weight products are responsible for the apparent instability of aromatic compounds from the power-factor standpoint.

The problem of determining the nature of the material responsible for the increased dielectric loss of bombarded hydrocarbons has been attacked from various angles. This included a number of d-c experiments. The use of porous membranes, as suggested by Doctor Hill, should prove of value in attempts to reduce the number of possible explanations for the behavior of the bombarded liquids.

The question raised by Mr. Halperin regarding the life expectancy and the reliability in service of cable in which some deterioration has already developed is of considerable interest. A definite answer to that question is of course impossible, but the question does lead to an interesting speculation, particularly in view of Mr. Halperin's statement that the cable has had an extremely low rate of failures attributable to the quality of the insulation, in spite of some carbonization and of wax formation. This speculation can best be explained in the following manner.

Wax in cables, resulting from ionization, is generally viewed with alarm, but this is possibly not the right attitude to take. Perhaps wax may be desirable, as it may be looked upon as the result of a natural self-defense of a cable against ionization occurring or continuing within the cable. If wax is readily formed, a protective coating will be produced over all surfaces of the voids in a short time. This coating decreases the volume of the voids, and with subsequent loading cycles additional polymerization products will be formed which add to the amount of wax in the voids. In this manner, ionization and resulting waxing can eventually lead to a reduced size of the affected voids which will not allow any further ionization to occur. Whether or not a cable can save itself in this manner from the ravages of internal ionization may be expected to depend essentially on what might be called "waxing ability" of the impregnating compound. If this waxing ability is low, the insulation might break down before sufficient wax can be formed to adequately reduce the size of the affected voids.

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[1] Hirshfeld, Meyer, and Connell, Minutes of the Forty-Fifth Annual Meeting of the Association of Edison Illuminating Companies, 1929, page 464.

Sensitivity of the Four-Arm Bridge

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MEMBER AIEE
(Deceased)

L. A. ZURCHER
ASSOCIATE AIEE

THE rapid increase in the use of a-c bridges for the measurement of electrical and nonelectrical quantities makes desirable a critical analysis of the performance characteristics of various types of bridge structures. The literature is replete with descriptions of multitudinous bridges and there is a great mass of analytical treatment and experimental data available concerning bridges designed for special purposes. The selection of a particular type of bridge is dictated by many conditions, the more important of which are:

(*a*). Sensitivity requirements
(*b*). Accuracy requirements
(*c*). Magnitude and characteristics of quantity to be measured
(*d*). Voltage and current requirements
(*e*). Frequency
(*f*). Availability of bridge components

Cases frequently arise when the last three considerations offer no obstacles and the selection of the bridge on the basis of the first three considerations is far from apparent. This is also true in the design of the so-called "universal" bridges which are employed for the measurement of several quantities over a wide range of values. Hence, it is recognized that different quantities and different ranges are most expeditiously measured by different bridges, and switching arrangements are incorporated for the transition from one type to another. An important question requiring a definite answer in this connection is, at what value of the unknown shall one type of bridge be switched into another type? This often involves considerable computation over a wide range of values and ratios before a satisfactory solution is obtained. A typical example of the amount of work necessary for a bridge design was presented to the Institute by Edwards and Herrington.[1]

The paucity of material treating sensitivity as related to the kind and magnitude of quantity being measured is surprising. Fischer[2,3] has given a general treatment of the problem, but his results are not in a form conducive to convenient comparison of various types of bridges. The sensitivity studies of Schering[4] apply only to the Schering bridge. Several years ago the first of the authors[5] presented a method whereby the locus of potential difference across the galvanometer terminals could be conveniently plotted in the form of a circle or in more complicated cases as the sum of several circles. A subsequent publication[6] demonstrated the applicability of the same method to the determination of galvanometer current.

The present paper treats the general problem of the unbalanced voltage appearing across the galvanometer terminals of any four-arm network as a function of the impedances of the arms in such a way as to show directly the effect of a slight change off the balance point for any of the bridge arms. The determination of sensitivity in connection with the open-circuit potential difference across the galvanometer terminals will be considered in this presentation. This problem is of greater interest than that of galvanometer current in view of the wide application of amplifiers operating into null detectors. Furthermore, the addition of a fifth arm involving galvanometer impedance brings in another variable which has no inherent relationship to the bridge structure and to a certain extent complicates comparison of various types of bridges.

General Four-Arm Bridge

The general structure of a four-arm bridge network is given in figure 1. The impedance arms, Z_1, Z_2, Z_3, Z_4, are assumed to be linear and bilateral. No mutual reactions between arms are considered to exist. The applied voltage E to the bridge is assumed to be constant. The unbalanced voltage across the galvanometer terminals is e; this voltage is given by:

$$e = E\frac{Z_1Z_3 - Z_2Z_4}{(Z_1 + Z_2)(Z_3 + Z_4)} \qquad (1)$$

It is more convenient to deal with the unbalanced voltage e' produced by unit potential across the bridge or

$$e' = \frac{e}{E} = \frac{Z_1Z_3 - Z_2Z_4}{(Z_1 + Z_2)(Z_3 + Z_4)} \qquad (2)$$

The sensitivity of a bridge structure with reference to any particular arm is the unbalanced voltage produced across the galvanometer terminals when the balancing arm is altered slightly from the true balance position. Any arm may be chosen as the balancing arm, say Z_3.

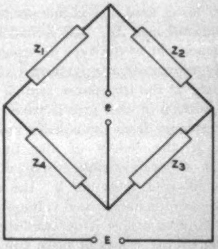

Figure 1. The general four-arm bridge

Let Z_3 be the correct value of this arm for balance, and let it change by a small amount to $Z_3 + dZ_3$. The change in the denominator on account of a slight variation of Z_3 is negligible because it enters as a small part of a sum. Hence:

$$e' = \frac{Z_1 \cdot dZ_3}{(Z_1 + Z_2)(Z_3 + Z_4)} \qquad (3)$$

For a fair comparison of sensitivity of various bridges the slight unbalance in Z_3 should be expressed as a fraction of Z_3. Let this fractional change be denoted by

$$\sigma' = \frac{dZ_3}{Z_3} \qquad (4)$$

To render the equation more tractable let the complex ratio of Z_1 to Z_2 be A.

$$A = \frac{Z_1}{Z_2} \qquad (5)$$

Then at balance:

$$\frac{Z_1}{Z_2} = \frac{Z_4}{Z_3} = A \qquad (6)$$

Introducing these substitutions the unbalanced voltage is:

$$e' = \frac{A}{(1 + A)^2} \cdot \sigma' \qquad (7)$$

The convenience of this expression lies in the fact that it consists of two independent factors. The first factor $A/(1 + A)^2$ may be called the "bridge factor" in that it depends on the type of

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[1] For all numbered references, see list at end of paper.

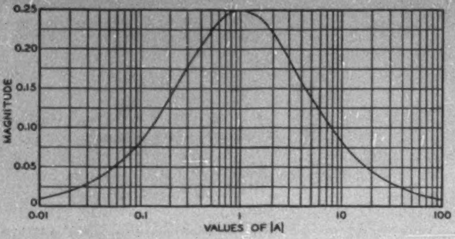


Figure 2. Magnitude of bridge factor

Curve of $A/(1+A)^2$ for $\theta = 0$ degrees $A = Z_1/Z_3 = |A| \underline{/\theta}$

bridge being used and is independent of the variable arm Z_3. The second factor is independent of the type of bridge and merely represents the fractional change produced in the impedance arm Z_3 when some portion of that arm is varied by a slight amount from the balance position. Thus, if the values of the function $A/(1+A)^2$ are available over a sufficient range, likewise those for σ', the determination of the unbalanced voltage across any four-arm bridge is accomplished by looking up the values of these two functions and taking their product.

The Function σ'

The function σ' which represents the fractional variation of impedance in the arm which is upset slightly from the balance position depends upon the manner in which this unbalance is produced. The more important cases arising in practice are:

(*a*). Series impedance arm
  1. Resistance and inductance
  2. Resistance and capacitance

(*b*). Parallel impedance arm
  1. Resistance and capacitance

In all these cases the ultimate variable to be considered is the variation of either in-phase or quadrature component. Hence, the function σ' will be studied in terms of a variable σ which will be $(dR)/(R)$, $(dL)/(L)$, or $(dC)/(C)$. In this way it is possible to obtain the fractional impedance variation σ' as a function of a slight change in any one component of a bridge arm. To increase the generality of the results, Q will be used to represent the ratio of reactance to resistance of the impedance arm. The results for these combinations are given in table I. The form for σ' in each case when the resistance is varied is:

$$\sigma' = \frac{\dfrac{dR}{R}}{1 \pm jQ} = \frac{\sigma}{1 \pm jQ} = \sigma \cdot \cos\theta \,\underline{/\mp\theta} \qquad (8)$$

where θ is the phase angle of the impedance arm. The maximum value of σ' occurs when $\theta = 0$, $Q = 0$; where the impedance is a pure resistance.

Likewise, the form for σ' in each case where the reactive component is varied is:

$$\sigma' = \frac{\pm\sigma}{1 \pm \dfrac{j}{Q}} = \pm\,\sigma \cdot \sin\theta \,\underline{/90^\circ - \theta} \qquad (9)$$

Here the maximum value of σ' occurs when $\theta = \pm 90$ degrees, $Q = \infty$, where the impedance is a pure reactance.

Obviously, the maximum value of σ' occurs where the direction of the change in impedance coincides with the impedance vector and this can only occur for pure reactance and for pure resistance arms. Inasmuch as the fractional upset off balance σ in the variable impedance arm expressed as a fraction of portion of the arm in which it occurs is usually taken at a small convenient value such as 0.001 or 0.0001, the determination of σ' is accomplished by merely multiplying the sine or cosine of the impedance phase angle by this fractional upset, σ.

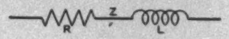
The Function $A/(1 + A)^2$

"RESONANT" TYPE BRIDGE

The type of bridge is characterized by the "bridge factor" $A/(1 + A)^2$. Inasmuch as A is a complex ratio of two passive impedances, its magnitude can vary from zero to infinity and its argument from ∓ 180 degrees to ± 180 degrees. These limiting values of angle are obtained when the impedances are pure inductive and pure capacitive reactances respectively. Thus, if the bridge arms are alternately composed of inductive and capacitive impedances, the sensitivity of the bridge approaches infinity as

Table I. The Function $\sigma' = dZ/Z$ for Various Impedances

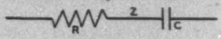
Resistance and Inductance in Series



$Z = R + jwL \qquad Q = wL/R = \tan\theta$

Variation of R, $\sigma = \dfrac{dR}{R}$	Variation of L, $\sigma = \dfrac{dL}{L}$
$\sigma' = \dfrac{\sigma}{1 + jQ} = \sigma\cos\theta\,\underline{/-\theta}$	$\sigma' = \dfrac{\sigma}{1 - j/Q} = \sigma\sin\theta\,\underline{/90^\circ - \theta}$
σ' increases as Q decreases	σ' increases as Q increases
$\sigma'_{\max} = \sigma = \dfrac{dR}{R}$ at $Q = 0$	$\sigma'_{\max} = \sigma = \dfrac{dL}{L}$ at $Q = \infty$

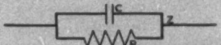
Resistance and Capacitance in Series



$Z = R - j/wC \qquad Q = 1/wCR = -\tan\theta$

Variation of R, $\sigma = \dfrac{dR}{R}$	Variation of C, $\sigma = \dfrac{dC}{C}$
$\sigma' = \dfrac{\sigma}{1 - jQ} = \sigma\cos\theta\,\underline{/\theta}$	$\sigma' = \dfrac{-\sigma}{1 + j/Q} = \sigma\sin\theta\,\underline{/90^\circ + \theta}$
σ' increases as Q decreases	σ' increases as Q increases
$\sigma'_{\max} = \sigma = \dfrac{dR}{R}$ at $Q = 0$	$\sigma'_{\max} = -\sigma = -\dfrac{dC}{C}$ at $Q = \infty$

Resistance and Capacitance in Parallel



$Z = R/(1 + jwCR) \qquad Q = wCR = -\tan\theta$

Variation of R, $\sigma = \dfrac{dR}{R}$	Variation of C, $\sigma = \dfrac{dC}{C}$
$\sigma' = \dfrac{\sigma}{1 + jQ} = \sigma\cos\theta\,\underline{/-\theta}$	$\sigma' = \dfrac{-\sigma}{1 - j/Q} = -\sigma\sin\theta\,\underline{/90^\circ - \theta}$
σ' increases as Q decreases	σ' increases as Q increases
$\sigma'_{\max} = \sigma = \dfrac{dR}{R}$ at $Q = 0$	$\sigma'_{\max} = -\sigma = -\dfrac{dC}{C}$ at $Q = \infty$

the arms are made more and more reactive and equal in value.

Let

$$A = A_d + jA_q \tag{10}$$

Then:

$$\frac{A}{(1+A)^2} = \frac{A_d + jA_q}{(1 + A_d + jA_q)^2} \tag{11}$$

The function equals infinity when $A_d = -1$ and $A_q = 0$ which is the condition described above. For lack of better name this type of bridge network may be called the "resonant" type and is characterized by having no finite limit to its sensitivity other than the physical limitations of obtaining purely reactive arms. The application of the resonant type of bridge has been described by Grover,[7] and is the only four-arm network which allows the ratio A to have a negative real component.

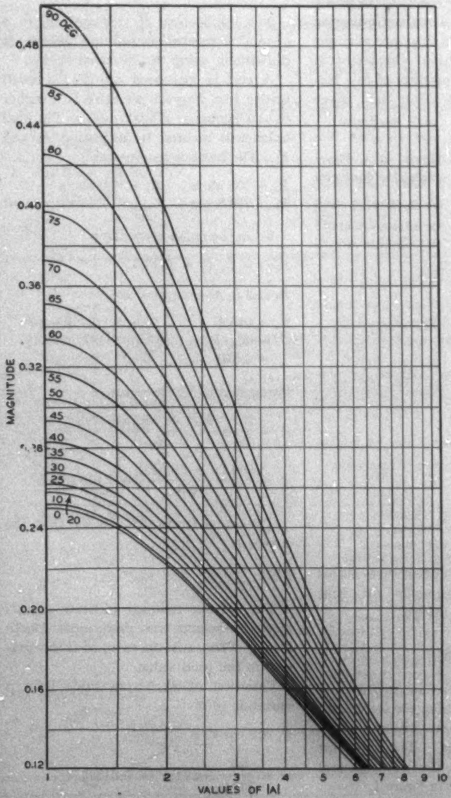


Figure 3A. Magnitude of bridge factor

Curves of $A/(1+A)^2$ for various values of θ $A = Z_1/Z_2 = |A| \underline{/\theta}$

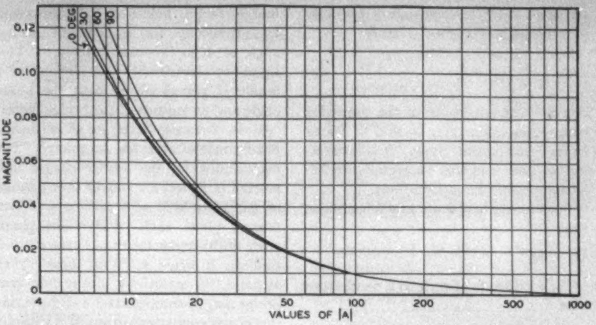


Figure 3B. Magnitude of bridge factor

Curves of $A/(1+A)^2$ for various values of θ $A = Z_1/Z_2 = |A| \underline{/\theta}$

"WHEATSTONE" AND "QUADRATURE" TYPES OF BRIDGES

The question of sensitivity may be further simplified by studying the limits of the function $A/(1+A)^2$ as A_d and A_q approach zero separately.

When the ratio A is of such character that its quadrature component A_q may approach or become zero, the bridge may be said to belong to the "Wheatstone" type.

$$A = \frac{Z_1}{Z_2} = \frac{|Z_1| \underline{/\theta_{z_1}}}{|Z_2| \underline{/\theta_{z_2}}} = \frac{|Z_1|}{|Z_2|} \underline{/\theta_{z_1} - \theta_{z_2}} \tag{12}$$

where θ_{z_1}, and θ_{z_2}, are the phase angles of the respective impedance arms. For A to be real

$$\theta_{z_1} - \theta_{z_2} = 0 \text{ degrees} \tag{13}$$

The maximum sensitivity for the real type is obtained when $Z_1 = Z_2 = Z_3 = Z_4$, and the maximum sensitivity becomes

$$e' = \frac{1}{(1+1)^2} \cdot \sigma' = \frac{\sigma'}{4} \tag{14}$$

This is the maximum sensitivity of the Wheatstone bridge, in terms of open-circuit potential difference across galvanometer terminals, with constant applied voltage, and is one of the cases analyzed by Fischer.[8] The fractional unbalance factor in the case of the pure resistance bridge is $\sigma' = (dR)/(R)$ and the maximum sensitivity when all four arms are equal is $(dR)/(4R)$ volts per volt of applied voltage. It is for this reason that when a bridge is operated in such a manner that the ratio A is real, it may be said to belong to the Wheatstone type.

When the ratio A is such that its real component may approach or become zero, the phase-angle relationship of adjoining impedances must be such as to allow approach to, or attainment of, the limiting value

$$\theta_{z_1} - \theta_{z_2} = \pm 90 \text{ degrees}$$

in this case the maximum sensitivity is

obtained when the magnitude of A is unity and the angle of A is 90. That is,

$$e' = \frac{j\sigma'}{(1 \pm j1)^2} = \frac{\sigma'}{2} \qquad (15)$$

or twice the sensitivity of the preceding case. This bridge may be said to belong to the "quadrature" type. It is interesting to observe in this connection the following practical considerations.

For a bridge to operate as a Wheatstone type

$\theta_{Z_1} = \theta_{Z_2}$

For a bridge to operate as a quadrature type

$\theta_{Z_1} - \theta_{Z_2} = 90$ degrees

Obviously, it is possible to have the same bridge satisfy both relationships if the arms are varied over a sufficiently wide range. For example, let Z_1 be a pure capacitance and Z_2 be a capacitance and resistance in series. Then as the resistance of Z_2 is reduced, θ_{Z_2} approaches θ_{Z_1} or 90 degrees and the bridge approaches the Wheatstone type. On the other hand, as the resistance in Z_2 is increased θ_{Z_2} approaches 0 degrees and the bridge approaches the quadrature type. This is one of the reasons why a particular bridge is more sensitive for the measurement of an impedance with a high Q and some other type of bridge is more sensitive for the measurement of an impedance with a low Q.

The "bridge factor" $A/(1 + A)^2$ is a function of both the magnitude and phase angle of the complex ratio of impedance arms A. It is a symmetrical function on either side of $A = 1$, as may be seen from figure 2, where the magnitude of the bridge factor has been plotted semilogarithmically for a constant phase-angle of A, in this case 0 degrees. This simplifies considerably the plotting of a family of curves giving both the phase angle and magnitude of the bridge factor, against the magnitudes of A with the phase angle of A as the parameter. The magnitudes of the bridge factor are plotted in figures 3A and 3B over a range of 0.001 to 1000 at increments of ten degrees phase angle of A. The phase angle of the bridge factor has been plotted similarly in figure 4. With these curves at hand, the sensitivity of any four-arm bridge may be computed for a slight variation of any component in any arm without resorting to computations involving complex quantities. Given the values of the impedance arms, it is necessary only to divide Z_1 by Z_2 or Z_4 by Z_3 to obtain A. The bridge factor is thus determined from the curves. Given the fractional upset in the variable arms, the factor σ' is obtained from the sine or cosine of the phase angle of the variable arms, according to equations 8 and 9 depending upon whether the resistive or reactive component is being changed. The product of this factor σ' and the bridge factor then, gives the sensitivity in open-circuit volts across the galvanometer terminals for unit voltage applied to the bridge.

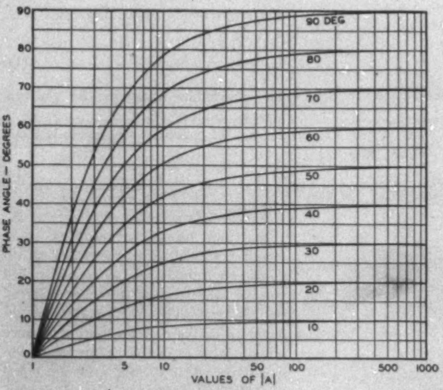


Figure 4. Phase angle of bridge factor

Curve of $\underline{/A/(1+A)^2}$ for various values of θ

$A = Z_1/Z_2 = |A|\ \underline{/\theta}$

Illustrative Analyses

The following analyses are to illustrate the method of determining the sensitivity of a four-arm bridge network for a given set of balance readings. The subscript notation corresponds to that of the general four-arm bridge shown in figure 1.

First, a pure resistance or Wheatstone bridge is used to measure an unknown resistance, R_1. The balance readings are:

$R_2 = 300$ ohms
$R_3 = 733.8$ ohms
$R_4 = 600$ ohms

From the balance equation:

$R_1R_3 = R_2R_4$
$R_1 = (300)(600)/733.8 = 245.3$ ohms and
$A = Z_4/Z_3 = 600/733.8$

The magnitude of the bridge factor is the same for $1/A$ as for A. Therefore:

$1/A = 733.8/600 = 1.223$

The bridge factor from the curves in figure 3A is 0.2475.

$\sigma' = \sigma = 0.1/733.8 = 0.000136$

Therefore:

$e' = (0.000136)(0.2475) = 33.7$ microvolts per volt

The application of this method to a general four-arm impedance bridge is illustrated, using the Maxwell bridge.

A coil is measured on the Maxwell bridge (for diagram see table II, number 6) at a frequency of 1,000 cycles. The final balance is secured by adjusting R_3 and C_3. The balance readings are:

$R_2 = 300$ ohms $\quad R_4 = 600$ ohms
$R_3 = 733.8$ ohms $\quad C_3 = 0.6598$ microfarad

From the balance equation

$R_1R_3 = L_1/C_3 = R_2R_4$

R_1 and L_1 as computed are:

$R_1 = 245.3 \qquad L_1 = 0.1187$ henrys
$Q = wL_1/R_1 = (6283.2)(0.1187)/245.3$
$= 3.040$

Using Z_4 and Z_3, the value of A is:

$$A = \frac{Z_4}{Z_3} = \frac{R_4(1 + jwC_3R_3)}{R_3}$$

$$A = \frac{600\ (1 + j\ 3.040)}{733.8} = 2.616\ \underline{/71.8^\circ}$$

The bridge factor $A/(1 + A)^2$ from the curves is

$0.276\ \underline{/-35.6^\circ}$

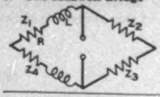
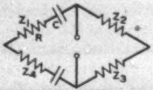
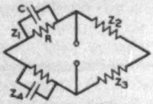
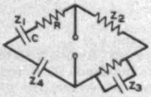
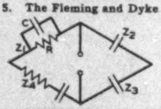
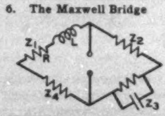
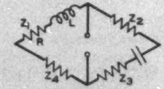
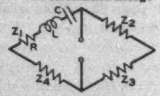
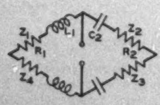
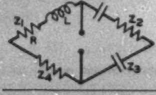
The balance readings indicate adjustments for balance were made in the fourth place. Then σ is the ratio of this variation to the total value.

Variation of R_3: from table I for a variation of R

$\sigma' = \sigma \cos\theta\ \underline{/\theta}$

$$\sigma = \frac{0.1}{733.8} \cos 71.8^\circ = 0.31233$$

Table II. Types of Bridges

1. The Maxwell Bridge		$\theta_{Z_2} = 0^\circ$ Quadrature Type High Q $WL \gg R$ $\theta_{Z_1} \cong 90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 90$ deg Wheatstone Type Low Q $WL \ll R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
2. The Wien Bridge		$\theta_{Z_2} = 0^\circ$ Quadrature Type High Q $1/WC \gg R$ $\theta_{Z_1} \cong -90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong -90$ deg Wheatstone Type Low Q $1/WC \ll R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
3. The Parallel Resistance Bridge		$\theta_{Z_2} = 0^\circ$ Quadrature Type High Q $1/WC \ll R$ $\theta_{Z_1} \cong -90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong -90$ deg Wheatstone Type Low Q $1/WC \gg R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
4. The Schering Bridge		$\theta_{Z_1} = -90$ deg $\theta_{Z_2} = 0$ deg Quadrature Type High Q $1/WC \gg R$ $\theta_{Z_1} \cong -90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong -90$ deg Wheatstone Type Low Q $1/WC \ll R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
5. The Fleming and Dyke Bridge		$\theta_{Z_2} = -90$ deg $\theta_{Z_3} = -90$ deg Quadrature Type Low Q $1/WC \ll R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 90$ deg Wheatstone Type High Q $1/WC \gg R$ $\theta_{Z_1} \cong -90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
6. The Maxwell Bridge		$\theta_{Z_2} = 0$ deg $\theta_{Z_4} = 0$ deg Quadrature Type High Q $WL \gg R$ $\theta_{Z_1} \cong 90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 90$ deg Wheatstone Type Low Q $WL \ll R$ $\theta_{Z_1} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
7. The Hay Bridge		$\theta_{Z_2} = 0$ deg $\theta_{Z_4} = 0$ deg Quadrature Type High Q $WL \gg R$ $\theta_{Z_1} \cong 90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 90$ deg Wheatstone Type Low Q $WL \ll R$ $\theta_{Z_1} \cong 90$ deg $\theta_{Z_1} - \theta_{Z_2} \cong 0$ deg
8. The Resonance Bridge		$\theta_{Z_1} = 0$ deg $\theta_{Z_2} = 0$ deg $\theta_{Z_3} = 0$ deg $\theta_{Z_4} = 0$ deg Wheatstone Type Only
9. The Grover Bridge		Any Value of Q $\theta_1 - \theta_2 = \theta_4 - \theta_3$ Resonant Type Kind of Sensitivity at $Z_1 = Z_4 \cong \lvert Z\rvert \underline{/+90 \text{ deg}}$ and $Z_2 = Z_3 \cong \lvert Z\rvert \underline{/-90 \text{ deg}}$ is infinity Wheatstone Type $WL_1 \ll R_1$ $\theta_{Z_1} \cong 0$ deg $1/WC_2 \gg R_2$ $\theta_{Z_2} \cong 0$ deg $\theta_{Z_1} - \theta_{Z_2} = 0$ deg Quadrature Type For $\theta_{Z_1} - \theta_{Z_2} = \pm 90$ deg
10. The Owen Bridge		$\theta_{Z_3} = -90$ deg $\theta_{Z_4} = 0$ deg $\theta_{Z_4} - \theta_{Z_3} = 90$ deg Quadrature Type Only

and

$$\sigma' = \frac{0.1}{733.8}(0.31233)\,\underline{/-71.8^\circ}$$
$$= 0.000044\,\underline{/-71.8^\circ}$$

Therefore,

$$e' = \frac{A\cdot\sigma'}{(1+A)^2}$$
$$= (0.276)(0.000044)\,\underline{/-35.6^\circ - 71.8^\circ}$$
$$= 12.1 \text{ microvolts/volt } \underline{/-107.4^\circ}$$

Variation of C_3: From table I for a variation of C

$$\sigma' = -\sigma \sin\theta\,\underline{/90^\circ - \theta}$$

$$\sigma = \frac{0.0001}{0.6597}\sin 71.8^\circ = 0.94997$$

and

$$\sigma' = \frac{0.0001}{0.6597}(0.94997)\,\underline{/90^\circ - 71.8^\circ}$$
$$= 0.000144\,\underline{/198.2^\circ}$$

Therefore,

$$e' = (0.276)(0.000144)\,\underline{/198.2^\circ - 35.6^\circ}$$
$$= 39.7 \text{ microvolts/volt } \underline{/162.6^\circ}$$

It is to be remembered that this analysis is illustrative only. To make a thorough comparison of bridges and methods of balancing as applied to a given engineering problem, the factors mentioned in the opening paragraph must be considered.

THE METHOD APPLIED TO TEN TYPES OF BRIDGES

In table II is given a summary of the sensitivity analyses of ten types of four-arm bridges. Numbers 1, 2, 3, 4, 6, and 7 will approach either the quadrature type or the Wheatstone type for values of high Q or low Q respectively. Number 5 has the same type sensitivity except for high Q it is of the Wheatstone type and for low Q it is of the quadrature type. Number 8 is of the Wheatstone type only and number 10 is of the quadrature type only. Number 9, the Grover bridge, has theoretically an infinite range of sensitivity; not only may it become of the resonance type, but it may also, under certain conditions, take on the other two types of sensitivity.

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Discussion

W. Richter (A. O. Smith Corporation, Milwaukee, Wis.): This paper is an excellent contribution to our knowledge on a-c bridges and should prove very valuable to all those workers that are employing these. If the desired accuracy for the unknown is given, the tables published in the paper permit the quick determination of the unbalanced voltage due to a small change of any of the balancing resistors. A knowledge of the magnitude of this voltage on the other hand permits the proper choice of the null-detector, and the design of an amplifier, if needed. Knowing the input voltage for this amplifier will save time and effort, usually wasted in trying to make it more sensitive than required for the problem on hand.

The paper treats only the problem of finding the open-circuit voltage of the bridge, that is, it assumes that a detector with infinite or at least very high impedance is employed. This assumption can safely be made for a-c bridges, since the usual detectors of former years, such as phones and a-c galvanometers, are now generally replaced by vacuum tubes, or at least, a vacuum tube is placed between the bridge and the detector, thus imposing a negligible load on the bridge. For d-c bridges this does not hold true however, since a simple and reliable amplifier for d-c voltages of the order of a few microvolts has not appeared yet.

Between equations 13 and 14 the statement is made that for maximum sensitivity the four impedances should be alike. This statement, carried from one textbook to the next, is incorrect even for the case where the detector has finite impedance, but its incorrectness is particularly easily seen in the case treated in the paper under discussion. Equation 7 gives the unbalanced voltage e' in terms of A and σ'. A is the ratio Z_1/Z_2 which for balance must equal Z_4/Z_3, while σ' is the fractional change dZ_3/Z_3.

The expression (7) for e' becomes a maximum for $A = 1$, that is, $Z_1 = Z_2$ and $Z_4 = Z_3$, but evidently there is no need for Z_1 to be equal Z_4 and Z_2 to be equal Z_3, since in the equation 7 appears only A, but not the actual values of the four arms. Even without reference to the equation 7 it is easily recognized that in case of infinite detector impedance the potentials of the two points to which the detector is connected are only functions of the impedance ratios of the two branches, that is, functions of Z_1/Z_2 and Z_4/Z_3, but are independent of the actual values of these impedances.

The paper does not assign any symbol to the angle of the complex ratio A; in the second example, the angle of 71.8 degrees is as well the angle of A as of σ'. This might prove somewhat confusing to the person reading the paper for the first time. It might have been helpful to point out that this coincidence is due to the fact that in this particular example of the Maxwell bridge the angle of A happens to be equal but of opposite sign to the angle of Z_3 because the phase angle of Z_4 is zero.

L. A. Zurcher: W. Richter's discussion is a valuable contribution to this paper. Mr. Richter is right that the statement "The maximum sensitivity for the real type is obtained when $Z_1 = Z_2 = Z_3 = Z_4$," made in the paper between equations 13 and 14, is incorrect. Oliver Heaviside in his "Electrical Papers," volume 1, pages 3–12, derived equations which apply to the present discussion. He specified the detector resistance by e and the battery resistance by f. Corresponding to the positions of Z_1, Z_2, Z_3, Z_4 in this paper he had resistances of a, c, b, and d. Heaviside's statement from page 4 is "and if only d, e, and f are given, then for any value we give to c, there is a pair of values of a and b which constitutes the best arrangement for that value of c; and there will be a particular value of c which, with the corresponding values of a and b, will be the best arrangement for the given values of d, e, and f." The result of this analysis is given on page 7 and is

$$c = \sqrt{df\frac{d+e}{d+f}} \tag{9}$$

$$a = \sqrt{ef} \tag{10}$$

$$b = \sqrt{de\frac{d+f}{d+e}} \tag{11}$$

Applying this to the present case where e is large and f small compared to a, b, c, and d we find that

$$c = \sqrt{df\frac{d+e}{d+f}} = \sqrt{ef}$$

$$a = \sqrt{ef}$$

$$b = \sqrt{de\frac{d+f}{d+e}} = d$$

or for this case $c = a$ and $b = d$.

This corresponds to Mr. Richter's statement that e becomes a maximum for $A = 1$.

Further for the case where the detector has infinite resistance and the battery finite resistance the ratio of a to c is

$$\frac{a}{c} = \sqrt{\frac{ef}{df\frac{d+e}{d+f}}} = \sqrt{\frac{d+f}{d+e}\,\frac{e}{d}}$$

$$= \sqrt{\frac{d+f}{\left(1+\frac{d}{e}\right)d}} = \sqrt{1+\frac{f}{d}} = \frac{b}{d}$$

That is if the battery supplying voltage to the bridge contains an internal resistance, the condition for maximum sensitivity is that

$$\frac{a}{c} = \frac{b}{d} = \sqrt{1+\frac{f}{d}}$$

and also a and c should be as large as possible.

B. Hague in his "Alternating Current Bridge Methods," page 63, shows that Heaviside's equations apply to the a-c case

Demand-Meter Time Periods

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THE "demand meter" has been used for approximately 40 years. The function of this device is to measure the "maximum demand" of the load taken by any user of electric service. This quantity, in turn, is used by most utilities in their rates for such service to their larger customers.

Unfortunately, the time period over which this "demand" is measured has never been standardized. A one-minute "demand" is the minimum time the writer ever heard of actually being used and one hour is the maximum. Modern practice has crystallized generally on two time periods, 15 minutes and 30 minutes.

When the demand meter used is of the "block interval" type, which measures the arithmetic average of the load used over the specified time period (15 minutes or 30 minutes as the case may be), there is no difficulty in getting a definite and concrete idea of just what is meant by "maximum demand." However, the Code for Electricity Meters, which is sponsored among others by the Edison Electric Institute, recognizes not only the "block interval" type but also puts its stamp of approval on the type wherein time appears as an exponential function instead of an arithmetic function as it does in the "block interval" type. When time appears as an exponential function, the meaning of "maximum demand" is not so apparent as when it appears as an arithmetic function. It is the object of this brief discussion to point out the differences in indication of "maximum demand" when using these two types of demand meters, that is, an arithmetic average as compared to a logarithmic average. The authors also make a plea for standardization of the time period of all maximum demand measurements.

To quote from the Code for Electricity Meters:

> CLASS II. INTEGRATED-DEMAND METERS
>
> 16. An integrated-demand meter consists of a device in a combination with an integrating meter whereby the energy consumption as measured by the meter is registered from time to time in such a way that the maximum demand may be determined from the record. Two variants are recognized: . . . .
>
> CLASS III. LAGGED-DEMAND METERS
>
> 17. These are instruments so constructed as to require a certain time interval for the indication to reach the point corresponding to the value of the load. Two variants are recognized:
>
> (*a*). Those in which the speed of the indicator in moving up its scale under constant load, is constant, or at any load, is proportional to the load.
>
> (*b*). Those in which the speed diminishes with the time of the deflection. (The demand interval of class III*b* meters is ordinarily considered to be the time required for the instrument to indicate 90 per cent of the full value of a steady load which is thrown suddenly on it.)

It should be particularly noted that the character of the quantity indicated by any of the "Class II. Integrated Demand Meters" or the "Class III—(*a*)" meters is quite different from that indicated by the "Class III—(*b*)" meters. To express in mathematical terms the indications of first two of the above types, it may be said:

meter indication = average load over the specified time (1)

The Code for Electricity Meters recognizes that this quantity differs from the quantity indicated by the class III*b* meters as is shown by the following quotation from the code:

> PRACTICAL INTERPRETATION OF MAXIMUM DEMAND
>
> 19. In commercial practice the maximum demand of an installation or system is given by the record or indication of a demand meter of acceptable type, which is correctly installed, properly adjusted, and none of the errors of which exceeds the limits of commercial tolerance.

In figure 1, the area *mmnn* shows the extreme limits of the indications of demand meters of class II type when there is applied to such a meter any given amount of energy (kilowatt-hours) of a time duration of less than three meter periods. The heavy line *mm* represents the indication that will obtain when using the class III*a* type in measuring short-time-duration loads. In neither of these cases does the meter distinguish between loads whose time of duration is less than one meter period. For instance, a 100-kw load for 30 minutes will give an indication no different from a 200-kw load for 15 minutes, a 600-kw load for 5 minutes, or a 3,000-kw load for one minute. The arithmetic average of all these over a 30-minute period is exactly the same.

When we come to consider the indications given by the class III*b* meters, (an exponential time function meter) we find quite a different situation. The indication of this type meter when responding to a load having a given amount of energy in a given time may be expressed mathematically as follows:

$$\text{meter indication} = \frac{\text{watt-minutes}}{t}\left(1 - \epsilon^{-Kt}\right) \quad (2)$$

where

ϵ = base of Napierian logarithms
t = time (minutes) of load application
K = an adjustable constant

In figure 1, curves *A*, *B*, *C*, *D*, and *E* represent the indications of a class III*b* demand meter when a given amount of energy (kilowatt-hours) is applied during any time period from zero to three times the time period of the meter. These five curves are simply a plot of meter indication against time as given by equation 2. These five curves differ only in the value of *K*. If *K* = infinity, it is obvious that equation 2 reduces to indication = watts (curve *A*). If *K* = 4.605, we have curve *B;* the indication will reach 99 per cent in one time period. If *K* =

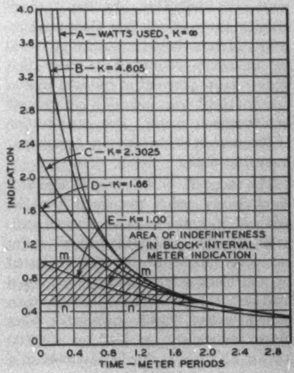

Figure 1

Paper number 39-72, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 10, 1938; made available for preprinting January 6, 1939.

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Mr. Sprole is responsible for the appendix.

2.3026, we have curve *C;* the indication reaches 90 per cent in one time period. If $K = 1.66$, we have curve *D;* the indication reaches 81 per cent in one time period. If $K = 1$, we have curve *E;* the indication reaches 63.2 per cent in one time period.

The value of the constant K is adjustable (by the maker *or* user) to any value desired within reason. The Code for Electricity Meters states that "ordinarily" the time period of class III*b* meters shall be taken as the time to reach 90 per cent of final value.. This would mean curve *C* in figure 1. The authors would suggest that the word "ordinarily" be omitted from this section of the code. As the code stands at present, the meter user would be justified in assuming that he is at liberty to use some value of K other than 2.3026 which gives the 90 per cent registration at full time. The writer happens to know that in some cases a value of $K = 4.605$ has been used. As clearly indicated in figure 1, this value of K is apt to give an excessive overregistration when the time of load application is less than about 99 per cent of one meter period. In thermal demand meters or in any other type wherein time appears as an exponential function, the time period of the meter is a matter of definition. In the authors' opinion, the wording of the Code for Electricity Meters should be such that it will be impossible to install a meter that arrives at 90 per cent of its final indication in 15 minutes and call it a 30-minute or a 60-minute meter. Proper protection of the users of electric service demands at least this much.

The value $K = 1$ (curve *E*, figure 1) is obviously much too small a value. With $K = 1$, the value of demand indicated by the class III*b* demand meter can never be greater than that indicated by the block interval type—even for a load of 1,000 times for 0.001 of the time period—unless "peak splitting" takes place. Obviously, a load of 100,000 kw for 1.8 seconds should pay more of a demand charge than a load of 100 kw for 30 minutes, although the energy contained in both these blocks of load is exactly the same. Since in the class III*b* demand meter, the time period is a matter of definition, it seems to the authors that the code should leave no doubt concerning the percentage of final reading to be taken as the nominal time period of such a meter. In other words, the definition should be definite.

The authors have included curve *D* ($K = 1.66$) for the purpose of raising a question concerning ammeter versus wattmeter performance. Class III*b* demand meters may be made available in ammeters as well as wattmeters. The time to reach 90 per cent of final reading has nearly always been taken as the nominal time period of the ammeter as well as the wattmeter. It should be noted, however, that the ammeter has a scale of squares while the wattmeter scale is uniform. When an ammeter has reached 90 per cent of its final reading, it has reached only 81 per cent (90 per cent squared) of its final angular deflection. Therefore, if we stick to 90 per cent of final reading as the proper definition of time period for both ammeters and wattmeters, it means that a given structure cannot be used for both instruments. For instance, a structure which, when used as an ammeter will arrive at 90 per cent of its final reading in 30 minutes, will, when used as a wattmeter, require approximately 42 minutes to arrive at 90 per cent of its final reading. This is not a serious matter since adjustment of the time period is not difficult. But if it is considered desirable that a given structure may be available for use either as an ammeter or wattmeter without change, the definition of what constitutes the time period of either the wattmeter or the ammeter must be changed; either the wattmeter time period must be taken as the time to arrive at 81 per cent of final reading (curve *D*-figure 1) or the ammeter time period must be taken as the time to arrive at 95 per cent of its final reading.

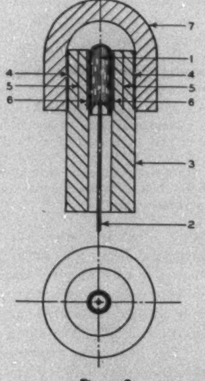

Figure 2

So long as "maximum demand" is measured by class II or class III*a* demand meters, there will always be an urge on the part of the utility to adhere to a comparatively short time period for demand measurement. Many of the modern uses of electric service lead to large loads of a relatively short time duration—welding for instance. If a customer has a load of any character which has a high value for a time period of say five or ten minutes, the utility naturally wishes to obtain compensation for the duty of supplying these high loads for relatively short time periods. If the utility has a choice between a 15-minute and a 30-minute demand period, the tendency will be to adopt the lower time period because of the desire to secure adequate compensation for supplying these short-time high-peak loads. If the demand measurements are made by means of the class III*b* type of demand meter, this tendency to choose the short time periods for demand measurement does not exist—or at least not to the same extent. The class III*b* demand meter automatically recognizes the time of load duration. This is clearly shown by curves *A*, *B*, *C*, *D*, and *E* of figure 1. These curves all show that the shorter the time during which a given amount of energy is used the higher will be the demand reading.

Some experimental work which one of the authors has been carrying on during the last ten years may be of interest to the users of demand meters and aid them to settle this question of the proper time period to adopt as standard for modern demand meters. Figure 2 shows diagrammatically the setup with which he has been experimenting. In figure 2, 1 is a reservoir containing an expansible liquid; 2 is a capillary tube which conveys this liquid to an indicating mechanism (not shown); 3 is a mass of insulating material (the experimenter is using bakelite), in one end of which are embedded resistances 4, 5, and 6; 7 is a mass of material, preferably metal, which is used for the purpose of storing the heat that is liberated in the resistances 4, 5, or 6. If the heat generated in the resistances 4, 5, or 6 at a given constant rate is diffused instantly throughout the mass being heated, it can be proved mathematically that temperature rise of the entire mass follows an exponential law. That is

$$T = T_1 (1 - \epsilon^{-Kt}) \qquad (3)$$

where

T = the temperature rise of the mass at any time

T_1 = the final temperature rise of the mass after the application of the constant heat rate for an infinite time

ϵ = base of Napierian logarithms
t = time
K = a constant

However, it is well known that heat does not and cannot diffuse instantly throughout any mass of matter that is being heated. Another phenomenon—diffusivity—enters the picture. If the diffusivity of the materials making up the entire mass being heated is known, the rate of temperature rise of any particular part of the mass being heated may be calculated mathematically (see appendix). However, the mathematical solution so arrived at is rather complicated and the authors prefer to discuss results in words rather than in mathematical formulas.

It is obvious that if the location of the heater is that shown as 4, figure 2, the heat generated therein is more quickly conducted to the mass 7 than to the heat-sensitive member 1. Such a location of the heater results in a meter performance similar to that shown as curve *A*, figure 3. In fact, curve *A*, figure 3 is the actual curve of performance of a thermal wattmeter first produced in 1917. (For complete description, see "The Character of the Thermal Storage Demand Meter," AIEE TRANSACTIONS, volume 37, 1918, pages 189–210.) The heater location of the wattmeter described in the reference simulated that of 4 in figure 2 herein. The maximum deviation from the theoretical response, assuming instantaneous diffusion, is nearly 30 per cent. If now the heater location be made that shown diagrammatically as 6 in figure 2 herein, it is obvious that the heat-sensitive member 1 will be affected in advance of the remainder of the total mass being heated. Location 6 in figure 2 herein results in a meter performance shown as curve *B*, figure 3. In this curve, the deviation from theoretical response, assuming instantaneous diffusion, is about the same as in curve *A*, figure 3, but now the deviation is above that for instantaneous heat diffusion instead of below, as it is in curve *A*, figure 3. If the heater location is that shown as 5, figure 2, the diffusion to 1 and 7 is very nearly at the same rate and the resulting performance is close to the theoretical—curve *C*, figure 3. By interposing additional thermal resistance between the heater and the mass 7, curve *B*, figure 3, may be caused to rise still further during the early moments of load application if desired.

The authors would like to point out that the actual curve of the heating of generators, motors, transformers, and other electrical equipment under actual loading conditions is more nearly like curve *B* of figure 3, than any of the other curves of this figure. The phenomenon of diffusivity occurs in actual electrical equipment even to a greater extent than in the structure shown in figure 2. The windings of any electrical equipment under load will heat up in advance of the equipment as a whole. Heat is diffused from the windings to the other parts only after a lapse of time. Diffusion follows a law of nature which cannot be repealed. So long as we must necessarily depart from the assumption of instantaneous diffusion, the authors would suggest that the departure be in the direction that we find in actual electrical equipment, namely, curve *B* of figure 3.

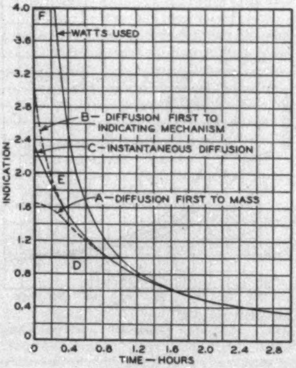

Figure 3

In view of the modified law of response that may be secured by the means described above, the authors would like to suggest the advisability of modifying the existing Code for Electricity Meters so that it calls for a definite time period for all demand meters. The relative demand indications as given by a thermal demand wattmeter as described above and a standard class II or class III*a* demand meter of one-hour time period may be seen from an inspection of figure 3. The horizontal line *D* of figure 3 gives the indication of a one-hour class II or class III*a* demand meter, provided it does not "split the peak." This compared with curve *B* gives the relative indications of the two types. During the first instant of load application, the class III*b* type wattmeter will register at a rate about three times that of class II or class III*a*. The rate of registration of the former remains above the latter for approximately 53 minutes. After the lapse of 53 minutes the class II or class III*a* type meter indicates a higher value than the class III*b*; provided there is no "peak splitting," the maximum excess of the former above the latter is ten per cent after exactly one hour of load application. After one hour, the difference decreases and after about $2^{1}/_{2}$ hours, the two types will read the same values. However, the above comparison is of little practical value since the number of demand meters of the class II or class III*a* type in actual use having a one-hour time period is practically nil.

A much more important comparison is one between a one-hour class III*b* type and a 30-minute class II or class III*a* type. This is given in figure 3 by comparing curve *B* with the line *E*. Comparing these, it will be noted that during the first instant of load application, the former registers at a rate approximately 50 per cent higher than the latter and remains higher during the first 11 minutes of load application. From 11 minutes to 30 minutes of load application, the class II or class III*a* will indicate considerably higher values than the class III*b*—assuming no "peak splitting"—the maximum excess of the former over the latter occurring after 30 minutes and amounting to approximately 47 per cent. After 30 minutes, the indications of the two types approach each other rapidly and become the same after about $2^{1}/_{2}$ hours of load application. It is impossible to say which type would indicate the higher value. This will depend entirely upon the character of the load during maximum and upon whether "peak splitting" occurs. It is the authors' opinion that in general the two types will not be far apart in their indications.

The line *F*, figure 3, compared to the curve *B* shows the relative indications of a 15-minute class II or class III*a* to a one-hour class III*b* demand meter. In this case, the former will always read higher than the latter, unless the time of load application is exceedingly short and "peak splitting" is at a maximum—a practically impossible combination. However, the authors consider that 15 minutes is too short a time period for demand measurement, no matter what type of demand meter is used. Even with this time period, it will be noted that after $2^{1}/_{2}$ hours of load application the two types indicate the same value.

The authors would urge that the utilities give serious consideration to adopting uniformity of practice in the time period over which maximum demand shall be measured. They hope that the foregoing analysis will be of service to them in the adoption of such a uniformity of practice.

It was not until after the manuscript for the foregoing paper on "Demand Meter Time Periods" had been submitted that the writer learned that a committee under the chairmanship of Doctor J. Franklin Meyer of the Bureau of Standards had been appointed to revise the Code for Electricity Meters. If the authors had known at the time of preparing the manuscript that the Code for Electricity Meters was coming up for revision, their recommendation would have been definitely to fix the time period of the thermal demand wattmeter at the time required to arrive at 81 per cent of final indications (K = 1.66). The reason for this recommendation is that it reduces to probably a minimum the discrepancy between the indications of the two types of demand wattmeters.

Commenting further, it is so obvious as to need no further discussions that the two types of demand wattmeters should indicate the same values as nearly as possible. The differing fundamental principles underlying the two types make it impossible that the two types should *always* indicate the same values. Figure 4 shows a comparison between the two types when $K = 1.66$ as well as when $K = 1.151$. Judging from this comparison, it is the authors' opinion that the value $K = 1.66$ will *probably* give about as small a discrepancy between the indications of the two types as any value that could be chosen.

Figure 4 shows also the results of some tests recently made on a thermal wattmeter. The heavy solid line marked K = 1.66 represents the performance that would obtain if the diffusion of heat could be made instantaneous. The short dotted line represents the performance with diffusion to the mass at a normal rate. The long dotted line represents the performance that has been obtained by a design that involves a considerable reduction in the rate of diffusion to the mass. This long dotted line by no means shows the maximum departure from the solid line that can be obtained by reducing the rate of diffusion to the mass still further.

It is obvious that a meter performance which follows the long dotted line would overregister on short-time high-peak loads—such as a spot welder. The rate of heat diffusion cannot be made infinite. Diffusion cannot be made instantaneous, but it can be controlled by proper design. The authors consider it to be a part of the duty of Doctor Meyer's committee to fix the maximum amount by which the dotted-line performance may be permitted to depart from the solid-line performance.

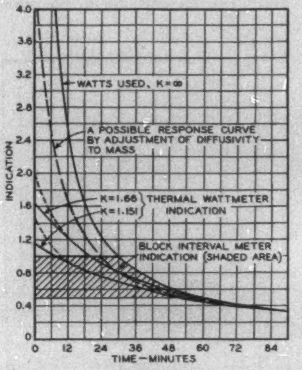

Figure 4

The advantage of being able to use a given structure either as an ammeter or wattmeter without change is so obvious as to need no further comments. If the same percentage of final reading is used to define the time periods of both ammeters and wattmeters, where time appears as an exponential function, as has been the general practice of the past, it means essentially that there is discrimination amounting to approximately 40 per cent of the ammeter time period between electric - service users whose maximum demand is measured by the thermal ammeter and those whose maximum demand is measured by the thermal wattmeter. The thermal demand ammeter antedates the thermal demand wattmeter by many years (Wright system, Brighton, England, about 1896). Wright adopted 90 per cent of final indication as his definition of time period for his demand ammeter. In the authors' opinion, this was a remarkably astute choice since it gives about as small a discrepancy between the "arithmetic" and the "logarithmic" averages as any value that could be chosen.

With the advent of the thermal demand wattmeter in 1917, the authors see no justification for continuing the discrimination between the ammeter user and the wattmeter user that was brought about by adopting the same percentage of final reading for both instruments.

In view of the foregoing discussion, therefore, the authors respectfully submit the following recommendations for the consideration of Doctor Meyer's committee:

1. The adoption of the time to arrive at 81 per cent of its final reading as the nominal time period of the thermal demand wattmeter.

2. The adoption of the time to arrive at 90 per cent of its final reading as the nominal time period of the thermal demand ammeter.

3. That 30 minutes shall be adopted as the time period for all demand meters, thermal and otherwise.

4. That Doctor Meyer's committee shall fix the maximum allowable departure to be permitted between the actual curve of response of thermal demand meters and the curve of response which would obtain under the assumption of instantaneous diffusion of heat and that the value so fixed shall become a part of the revised code.

Appendix

The equation of temperature rise versus time (equation 3) given in the paper assumes instantaneous diffusion of heat throughout the mass. As pointed out, this assumption introduces an erroneous concept in regard to the heating and cooling of mass. However, the mathematical expression so obtained can conveniently be handled in calculating approximate values.

In an effort to broaden this concept of temperature rise throughout a mass by introducing the diffusivity factor, reference is made to Ingersoll and Zobel in their book, "Mathematical Theory of Heat Conduction," and also the text, "Heat Transmission" by William H. McAdams. Both texts refer to Fourier's expression of thermal conductivity and derive from it the partial rate of temperature rise in a given direction as:

$$\frac{\partial\theta}{\partial t} = \frac{K}{\rho c_p}\left(\frac{\partial^2\theta}{\partial Z^2}\right) \tag{4}$$

Applying equation 4 to a slab of mass of thickness $2R$ having negligible surface resistance, McAdams shows the temperature rise as a function of time to be:

$$\theta = \Theta\left(1 - \frac{4}{\pi}\sum_{a=1}^{a=\infty}\frac{\epsilon^{-a^2\alpha t}}{a}\cdot \sin\, a\beta\right) \tag{5}$$

The boundary condition of equation 5 is the same as that for the expression given in equation 3, that is, $\theta = \Theta$ at $s = 0$ and $s = 2R$; $\theta = \theta_1$ at $t = 0$; and $\theta = \Theta$ at $t = \infty$.

Equation 4 may be expressed in the form of a general solution for the particular problem given by McAdams as:

$$\theta = \frac{\alpha}{\pi}\sum_{a=1}^{a=\infty} a \sin a\beta \cdot \int_0^t f(x)\epsilon^{-(t-x)a^2\alpha\left(\frac{2}{\pi}\right)^2} \tag{6}$$

It is to be noted in equations 5 and 6 that for a given mass, the value of β will depend upon the location of that particular point within the mass where the temperature rise is to be measured. Therefore, there exists for each point within the mass, a separate and slightly different exponential expression.

The mathematical series of equations 5 and 6 converges rapidly, and for large values of t, equation 5, approaches the expression given in the paper. The diffusion factor becomes less dominant in the solution as t increases, being negligible for values of t when θ is as small as 70 per cent Θ.

Thermal demand metering has in general been accepted as being a logical method for the measurement of demand due to the fact that the indication of these meters, and the heating of electrical equipment are both a function of the fundamental laws of heating and cooling. However, to set forth a specific temperature response curve for thermal meters to follow based upon the heating and cooling curves of electrical equipment would be quite impractical as a variety of thermal curves would result for different equipment, and in addition a wide family of curves would be obtained for any given equipment depending upon the point within the equipment where temperature was being measured.

It is important, however, that all thermal meters of a given classification follow the same exponential curve. Otherwise, thermal meters built by various manufacturers will not agree in their indication on rapid load variations, although it is true that they will register the same on a continuous applied constant load regardless of the exponential curve followed by the individual meters.

In taking steps to standardize on an exponential curve, the paper points out that in referring to the heating and cooling of electrical equipment, one can be guided by the fact that in general the conductors buried in the surrounding insulation have a more rapid temperature variation than the surrounding mass upon load variations. This statement bears considerable weight in deciding whether or not a thermal meter should have an initial rapid, or slow rise in indication upon load application. The authors refer to the exponential equation as a reference datum and to this extent the equation becomes quite useful.

Whatever the standardized exponential curve shall be, it inevitably must be one arbitrarily deduced and biased to some extent by the range over which present thermal-meter manufacturers can control their response. With the variety of exponential curves resulting from the most simple application of Fourier's equation, as illustrated in this appendix, there certainly must exist a curve that can be made satisfactory to all concerned and still be classified as an exponential curve.

θ = temperature at time t
θ_1 = temperature at time $t = 0$
t = time
K = conductivity
ρ = density
c_p = specific heat
Z = distance along Z axis
Θ = ultimate temperature of mass arrived at when $t = \infty$ under conditions of constant heat application
a = odd integers
$\alpha = \left(\frac{\pi}{2}\right)^2\left(\frac{K}{\rho c_p}\right)\left(\frac{1}{R}\right)^2$
$\beta = \left(\frac{\pi}{2}\right)\left(\frac{s}{R}\right)$
R = main thermal path or distance from the source of heat to the midplane, the midplane being the plane across which no heat passes
s = mean thermal path or distance from source of heat to point at which temperature is being measured. In the thermal meter the source of heat is considered to be the resistors, and temperature is measured within the liquid of the reservoirs
$f(x)$ = function of heat applied to mass corresponding to time x
ϵ = 2.718

Discussion

Sidney Withington (New York, New Haven, and Hartford Railroad Company, New Haven, Conn.): This interesting paper illustrates clearly many of the problems in design and utilization of demand meters, and is a valuable addition to the literature on the subject.

While the recommendation of the 30-minute time period for all demand meters is of interest, and in some respects logical, it is suggested that in certain services at least, this period is shorter than is desirable, in view of the characteristics of the services involved and the design characteristics of the supply and utilization equipment, and for this reason one-hour periods would be in many ways more logical than shorter periods, as standard. In this connection, the one-hour integrated demand period might be correlated with the clock-hour in the interest of simplification.

H. M. Witherow (General Electric Company, Lynn, Mass.): We agree with Dr. Lincoln as to the desirability of standardizing time interval and characteristics of demand meters. Such standardization would ultimately benefit both the utilities and the manufacturers. However, in arriving at standardized characteristics there are many factors which must be studied and given their proper value. Characteristics should be fixed only after a thorough study of these factors has been made and conclusions discussed with manufacturers and users of demand meters.

In most discussions regarding the agreement or lack of agreement between block interval and logarithmic demand meters a great deal of emphasis is placed upon the difference in registration on loads of short duration. These differences have been given much too much importance since any demand meter measures only approximately the many variables entering into the cost to serve. In considering standardization, short period characteristics should be considered of secondary importance.

Welding loads which call for large amounts of power for intervals of only a few seconds cannot be properly measured by any of the ordinary demand devices. Billing for this type of load which will reflect the cost to serve will ultimately be made on some other basis or at least on some measurement which is suitable for this type of load and which is quite different from the ordinary demand measurement.

The intermittent loads usually found which may have peaks of a few minutes duration might be considered a real problem if one central station served one customer. Where one central station and distribution system serves many customers these more usual short-time peaks have little or no effect on the system since the individual peaks are small compared to the capacity of the system and time diversity of the many customers tends to minimize their effect. Demand measurement may be considered as a method of reducing the combined sustained peaks rather than a means of penalizing the individual customer who may have a high peak of short duration. Many rate engineers now think of demand measurement in terms of promotional rates rather than in terms of penalty rates, and it is entirely proper that demand charges should be so considered.

In considering standardization of characteristics, most importance should be given to reasonable agreement on the more usual types of loads where peaks are normally sustained for longer periods. From the standpoint of promotional rates the time interval should be made as long as is consistent with the short-time rating of generating and distribution equipment.

There is little justification for a difference in the characteristics of logarithmic wattmeters and ammeters. The only reason for such a difference is convenience to the manufacturer, which usually has not been considered a sound basis of definition. If some certain characteristic can be defined as most suitable for measurement of demand in watts, this same characteristic should be just as desirable for the measurement of demand in amperes, volt-amperes, or any other unit.

In fixing the time interval for the characteristic of logarithmic meters, practical as well as theoretical considerations should be properly evaluated. For example, the time required for testing demand meters is quite important to the larger utilities. Within the past few years very satisfactory means have been developed for testing block-interval mechanisms whereby a complete check can be made within a few minutes regardless of the rated interval of the device. To my knowledge, no comparable method is available for testing thermal meters and if the ideal logarithmic meter is one reaching 81 per cent of its final indication in 30 minutes, the time required for test would be greatly increased over that required for testing similar meters now on the market. It is probable that such a meter would require about two hours to reach its final indication on steady load and an equal period would be required for it to cool off in order to check a second point.

Whenever logarithmic demand meters are discussed it seems to be taken for granted that one should point out that block-interval meters may split peaks of short duration and thus arrive at different indications for equivalent loads, depending upon where the fixed interval begins. This is a characteristic of the block-interval meter which is well recognized and which may cause some variation in reading on certain types of loads, but which, in general has little significance in demand measurement. In papers in which this possible variability is given prominence, the inference is that the logarithmic meter is perfect in this respect and that it will always give the same indication for equivalent loads. This is true if we assume that these equivalent loads are always applied in the same order. For example, let us assume that a customer has just two loads, one of which is three times the other, and that once in each 30-minute period they are applied in sequence for some short interval such as 5 minutes each. If the larger load always follows the smaller load then the logarithmic meter will repeat. However, if we reverse the sequence, quite different results are obtained. Recent tests on such a load showed a difference of over 20 per cent in the indication of a logarithmic meter, merely by reversing the order in which the loads were applied. Practically, this is just as important and has just as little significance as the split peaks of block interval meters. I would like to suggest that in future discussions these characteristics be given a place comparable to their significance so that the real point of the discussion will not be lost.

Albert J. Allen (Consolidated Edison Company of New York, Inc., New York): I want to congratulate Doctor Lincoln for his clear exposition of the manner in which the load-time curve of thermal-demand meters may be controlled.

In recommending a particular load-time curve as a single standard for thermal-demand meters, however, I believe that a greater step has been taken than is justified by the evidence at hand. In any event, the inclusion of this single standard, in the Code for Electricity Meters would set up restrictive clauses of a nature that have always been, and should remain, foreign to the main purpose of the code.

In my opinion, the code should remain broad enough to cover all acceptable types of demand meters, and as long as any such type is clearly described, and made subject to a sufficient number of tests to determine that representative samples of that type will perform in accordance with its stated characteristics, the purpose of the code is accomplished.

Any further step is now, and should remain, in the hands of the rate engineer. It is for him to decide which among the various types of demand measurement available best represents the cost of service. The code can be of great value in outlining what kinds of demand meters are available for use and in setting up tests to determine which manufacturer's types best perform in accordance with stated characteristics, but it would do a disservice if it restricted the use of any type of demand meter to a particular demand interval, without regard to the characteristics of the system on which it is to be used, or the load which it is to measure.

The difference in load measurement between lagged-demand meters as a class and integrated-demand meters as a class, both of which would remain as acceptable types, is much more pronounced than the difference between two lagged-demand meters having different characteristic curves, one reaching 81 per cent and the other 90 per cent of final indication in a demand interval. This, I believe, weakens the case for selecting either of these particular load-time curves as a single standard for lagged-demand meters.

P. M. Lincoln: Mr. Withington's suggestion for adopting one hour instead of 30 minutes as the standard time period for demand measurement is, in the writer's opinion, a step in the right direction. However, the writer believes that such a move is premature. The first step is the elimination of the 15-minute time period now quite widely used. If and when all demand periods have become 30 minutes, the next logical step would be to increase the time period for demand measurement to one hour.

The writer believes that the utilities would hesitate to take such a step so long as "block-interval" meters are used for demand measurement. In many of the modern uses of electric service, the average of the maximum 15-minute or 30-minute period within the maximum one hour would be materially higher than the average for the whole hour. Such a step would therefore mean essentially a reduction in rates. This is a question for each utility to consider on its own merits. The thermal demand wattmeter would recognize the higher rate of use of service during fractions of the maximum hour and with this method of measuring maximum demand, the writer sees no objection to the use of a one-hour time period.

Mr. Witherow deplores the emphasis placed on the difference in indication between the "block-interval" and the "logarithmic" types of demand meters. In view of the differing fundamental principles underlying the two types, it is not difficult for a utility to explain a difference in the indication of the two types to a user of service. Mr. Witherow does not suggest any logical explanation that the utility can give to a service user who finds a difference in indication of 5 per cent to 15 per cent (a possible 50 per cent) in the indications of two identical "block-interval" meters measuring the *same* load. Nor does he suggest any means by which the utilities may meet the situation when knowledge of the inherent inaccuracy of the "block-interval" demand meter has become generally known to the users of electric service.

In discussing the difference in registration on short-time loads between the "block-interval" and the thermal types of demand meters, Mr. Witherow states, "These differences have been given much too much importance since any demand meter measures only approximately the many variables entering into the cost to serve." In this, the writer disagrees with Mr. Witherow. The demand measurement is intended to assess the service user an amount which will reimburse the utility for its fixed charges (interest, depreciation, taxes, and insurance) and these in turn amount to approximately one-half of the total costs of rendering electric service. In the writer's opinion, it is impossible to give "too much importance" to obtaining an *accurate* measure of demand.

Mr. Witherow also intimates that billing for short-time loads—such as a spot welder—should be made "on some other basis or at least on some measurement which is suitable for this type of load and which is quite different from the ordinary demand measurement. In using the term "ordinary demand measurement," Mr. Witherow undoubtedly has in mind the block-interval demand meter. The writer would remind Mr. Witherow that the thermal-demand meter is not an "ordinary demand measurement." The thermal-demand meter recognizes the heating effect of any load, no matter what is its value or its time of duration. If all loads were steady, demand measurement would be simple; any sort of a wattmeter would effect an accurate measurement. It is only when load peaks occur that demand measurement calls for something more. That "something more" is the thermal-demand meter which the writer is advocating.

The writer notes with satisfaction Mr. Witherow's comment that "There is little justification for a difference in the characteristics of logarithmic wattmeters and ammeters." Presumably, therefore, he approves the writer's recommendation that the demand wattmeter's time period shall be defined as the *square* of the percentage of final value of the demand ammeter time period.

In commenting on the time required to test thermal demand meters as compared to the "block-interval" type, Mr. Witherow makes a real point. The writer has considered this difficulty at some length. In his opinion, the methods of testing this type meter should be somewhat modified to meet the very point that Mr. Witherow has raised. The writer would suggest that the utilities have on hand at all times a reasonable stock of thermal demand meters known to be correct. If suspicion arises concerning the accuracy of any meter in service, one of these test meters may be placed in series with it. Within two hours, at the utmost, the test meter should be reading correctly the load passing. If the tester cannot wait the necessary time, he may return the next day or the observations may be taken on the occasion of the inspector's next regular visit. If the two meters read the same values—no matter what that value—the subscriber's meter is correct; if there is a difference, the subscriber's meter may readily be adjusted to be correct.

And while we are on the subject of testing, the writer would like to point out that the Code for Electricity Meters recommends the periodic testing of all class I and class II demand meters at intervals of one year. For class III*b* demand meters, the recommended test period is "not to exceed five years." It also may be of interest to observe that in Canada where the thermal demand meter has been standard since 1923, these meters are sealed by the Canadian Government for a period of six years. The simplicity of the thermal demand meter and the absence of any complicated mechanism have proved this practice to be satisfactory in Canada.

Subharmonics in Circuits Containing Iron-Cored Inductors—II

IRVEN TRAVIS
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Synopsis: This paper is an extension of the work reported in a paper of the same title by the writer and C. N. Weygandt.[1]

The production of subharmonic oscillations in a series circuit consisting of a capacitor and an iron-cored inductor is studied by the method of matching boundary conditions. The calculations are carried out by means of a new mechanical calculating device, and are verified by differential-analyzer solutions.

A sufficient, but not necessary, criterion for stability is deduced. Some consideration is given to the effect of resistance in the circuit.

I. Introduction

IT IS assumed that the reader is familiar with reference 1. It will be recalled that the method of matching boundary conditions was used in that paper. The method was idealized to a considerable extent in order that certain mathematical difficulties might be avoided. This resulted in an analysis which was convenient in those cases in which it applied, but which was of very limited scope. The idealizing assumptions were:

1. The winding resistance of the inductor was taken equal to zero.
2. All hysteresis effects in the inductor core were neglected.
3. Eddy currents in the inductor core were neglected.
4. It was assumed that the saturation curve of the iron could be represented by the three straight lines shown in figure 1.
5. The analysis was restricted to those cases in which the effect of capacitance *during operation in the saturated region* could be neglected.

Of these assumptions the fifth imposed the most serious limitation. The values of parameters ordinarily encountered in series capacitor installations in transmission systems, and in many other practical cases, fall outside the range over which this assumption is valid. The assumption 4 represents the actual phenomenon with satisfactory accuracy; the assumption that the current is zero over the unsaturated region introduces no great error inasmuch as the unsaturated inductance is usually about 40 times the saturated inductance. The first three assumptions remove all dissipation from the circuit. Although this may affect the stability of various modes of oscillation, it is felt that the effect upon wave form is slight. In this paper assumptions 1 to 4 are retained but the effect of capacitance in the saturated region is considered.

II. Excursion in the Saturated Region

Since the analysis is to include the effect of capacitance during operation in the saturated region, the equation which holds in that region is

$$L\frac{d^2q}{dt^2} + \frac{q}{C} = E\sin(t+\beta_k)^* \tag{1}$$

subject to the boundary conditions

$$t = 0 \qquad \frac{dq}{dt} = 0 \qquad q = Q_k \tag{2}$$

In equations 1 and 2, the symbols have the same significance as in reference 1.

The solutions of equation 1 for charge and current, after inserting boundary conditions, are:

$$q = \left(Q_k + \frac{CE\sin\beta_k}{LC-1}\right)\cos\frac{t}{\sqrt{LC}} + \frac{CE\sqrt{LC}\cos\beta_k}{LC-1}\sin\frac{t}{\sqrt{LC}} - \frac{CE}{LC-1}\sin(t+\beta_k) \tag{3}$$

$$i = \frac{CE\cos\beta_k}{LC-1}\cos\frac{t}{\sqrt{LC}} - \frac{1}{\sqrt{LC}}\left(Q_k + \frac{CE\sin\beta_k}{LC-1}\right)\sin\frac{t}{\sqrt{LC}} - \frac{CE}{LC-1}\cos(t+\beta_k) \tag{4}$$

These equations hold throughout opera-

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The author wishes to express his appreciation to Cornelius Weygandt for valuable suggestions, to M. E. Nelson for his excellent work in constructing the calculating mechanism, and in particular to Doctor J. A. Shohat of the mathematics department, University of Pennsylvania, for his aid in connection with appendix III.

[1] For all numbered references see list at end of paper.

*Time is measured in radians of the impressed sinusoid.

The writer disagrees completely with Mr. Witherow's contention that two loads each of five minutes duration, one three times the other in value, first in one sequence and then in the other, are "equivalent" loads. They most decidedly are *not* "equivalent" loads. The best possible means of proving this lack of equivalence is to examine the temperature rise of the equipment that carries such loads. The rising sequence will invariably cause a higher temperature rise in the equipment carrying such loads than will the falling sequence. The writer considers it to be one of the outstanding merits of the thermal demand wattmeter that it thus recognizes the lack of equivalence of two such loads as Mr. Witherow has described. The thermal demand meter recognizes this lack of equivalence by the same fundamental law of nature as does the equipment that carries the load.

Commenting now on Mr. Allen's contribution the writer quite agrees with Mr. Allen when he says, "The difference in load measurement between lagged-demand meters as a class and integrated-demand meters as a class, both of which would remain as acceptable types, is much more pronounced than the difference between two lagged-demand meters having different characteristic curves, one reaching 81 per cent and the other 90 per cent of final indication in the demand interval."

However, Mr. Allen seems to have missed one of the main points in the writer's paper. The writer considers it of the utmost importance that the Code for Electricity Meters shall recognize the inherent difference between the thermal demand wattmeter and the thermal demand ammeter. To recognize this inherent difference, the time period of the wattmeter *must* be defined as the square of the time for the thermal demand ammeter to arrive at any given percentage of final value. The fundamental laws of nature dictate at least this much. The exact percentage of final value by which to define time and just what this time shall be are matters which are in the hands of the lately appointed committee to revise the Code for Electricity Meters. But whatever time is adopted or whatever percentage is adopted, the percentage of the wattmeter time period *must* be the *square* of the ammeter time period.

The writer still adheres to his recommendation that 30 minutes be adopted as the time period for all demand measurements. Comparisons between the rates of various utilities are thereby made much simpler and confusion will be avoided. However, the writer does not consider this to be an *essential.*

tion in the saturated region, that is, until the flux linkage in the reactor has been reduced again to the value it had when operation started in the saturated region.

The current at a transition from one region of operation to the next is always zero, hence the conditions which obtain at the instant t_k, at which equations 3 and 4 cease to hold, are:

$$Q_{k+1} = \left(Q_k + \frac{CE \sin \beta_k}{LC - 1}\right) \cos \frac{t_k}{\sqrt{LC}} + \frac{CE\sqrt{LC} \cos \beta_k}{LC - 1} \sin \frac{t_k}{\sqrt{LC}} - \frac{CE}{LC - 1} \sin (t_k + \beta_k) \quad (5)$$

$$0 = \cos \beta_k \cos \frac{t_k}{\sqrt{LC}} - \frac{1}{\sqrt{LC}} \times \left(\frac{LC - 1}{CE} Q_k + \sin \beta_k\right) \sin \frac{t_k}{\sqrt{LC}} - \cos (t_k + \beta_k) \quad (6)$$

in which Q_{k+1} is the charge at the end of operation in the saturated region. Q_{k+1} and t_k are the values which must be used as boundary conditions in the solution of the differential equation for the next traverse of the unsaturated region. The time t_k must be determined from equation 6; then Q_{k+1} may be determined from equation 5. Note that t_k is the smallest angle greater than zero which satisfies equation 6.

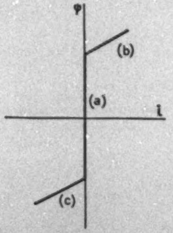

Figure 1. Idealized saturation curve

Since the current is always zero at a transition point, the charge and the phase angle of the electromotive force at transition are sufficient boundary conditions. If the saturated region is entered with a charge Q_k and an electromotive force having the phase angle β_k, then the saturated region will be left when the charge has changed to Q_{k+1} and the phase angle has become $\beta_{k+1} = \beta_k + t_k$. Let us associate corresponding charges and phase angles to form complex numbers. Denote $Q_{k+1} \angle \beta_{k+1}$ by $\mathbf{Q}_{k+1}$ and denote $Q_k \angle \beta_k$ by $\mathbf{Q}_k$. Then the effect on the boundary conditions of an excursion in the saturated region may be described by the equation:[*]

$$\mathbf{Q}_{k+1} = f_s(\mathbf{Q}_k) \quad (7)$$

where f_s denotes the functional relationship given by equations 5 and 6. Figure 2 shows examples of contours in the $\mathbf{Q}_k$ plane and the corresponding contours in the $\mathbf{Q}_{k+1}$ plane. A discussion of these contours and the nature of the function f_s is given in appendix I.

III. Excursion in the Unsaturated Region

From reference 1, equation 21, the flux linkages during operation in the unsaturated region are given by

$$\psi = -E \cos t - \frac{Q_0}{C} t + \psi_0 + E \cos T_0 + \frac{Q_0 T_0}{C} \quad (8)$$

in which ψ_0 is $\pm\psi_s$, T_0 is the angle of the electromotive force at the instant of entering the region, and Q_0 is the charge at entering. Denote by Q_m and β_m the charge and angle at entering the unsaturated region, then the charge and angle at leaving are Q_{m+1} and β_{m+1}. These values are given by

$$Q_{m+1} = Q_m \quad (9)$$

$$\cos \beta_{m+1} + \frac{Q_m}{CE} \beta_{m+1} = \cos \beta_m + \frac{Q_m}{CE} \beta_m + x \quad (10)$$

where x has the value $+2\psi_s/E$ when the transition is from the upper to the lower saturated region, the value $-2\psi_s/E$ when the transition is from the lower to the upper saturated region, and the value 0 when ψ re-enters the region from which it came.

The effect on the boundary conditions of an excursion in the unsaturated region may be described by the equation

$$\mathbf{Q}_{m+1} = f_u(\mathbf{Q}_m) \quad (11)$$

in which the complex numbers represent charge and phase angle of electromotive force entering and leaving the region, and f_u denotes the functional relationship given by (9) and (10). The footnote discussing equation 7 applies equally well to equation 11.

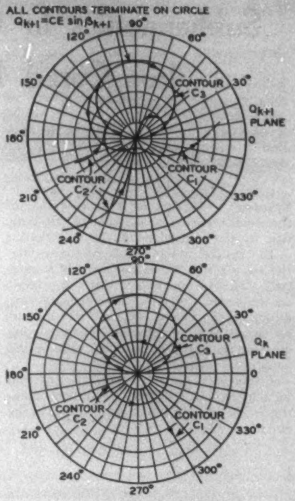

Figure 2. Examples of contours

IV. Recurrent Boundary Conditions

A subharmonic exists when the boundary conditions after a given succession of traverses of the ψ versus i characteristic are found to be substantially recurrent. The term *substantially* is used because it is believed that, except in unusual circumstances, an oscillation which over short intervals seems to be recurrent actually has superimposed upon it a perturbation. The superimposed perturbation may be of much lower frequency than the approximately recurrent phenomenon, or indeed may not be periodic at all.

Disregarding minor deviations due to the above mentioned perturbation, we may express the condition for a subharmonic oscillation mathematically by the equation

$$\mathbf{Q} = f_s f_u \ldots f_s f_u f_s f_u \mathbf{Q} \quad (12)$$

that is, if, by operating successively and alternately with the functions f_u and f_s, a given complex number transforms into itself, then that complex number gives the charge and phase angle of electromotive force for a subharmonic oscillation.

The operation indicated in equation 12 cannot be carried out analytically since

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[*] There is one point in connection with this method of expressing the problem which requires amplification. The charge Q_k may be negative. Since the modulus of a complex number cannot be negative, the question arises as to whether or not it is permissible to represent such a negative sign by a phase angle of 180 degrees in the usual way for complex numbers. Suppose $Q_k = -A$, where A is positive, and $\beta_k = \theta_a$. Let the resulting value of $Q_{k+1} = B$ and of $\beta_{k+1} = \theta_b$. Now if the complex number $A/\underline{\theta_a + 180^\circ}$ is used to represent $\mathbf{Q}_k$, it is readily seen from equations 5 and 6 that the corresponding values of β_{k+1} and Q_{k+1} are $\theta_b + 180^\circ$ and $-B$; but these would be represented by the complex number $B/\underline{\theta_b}$ which agrees with the previous result. *Mathematically*, therefore, the scheme works; it is useful providing the duality of *physical interpretation* can be rendered particular by other considerations. That this can be done will presently become apparent.

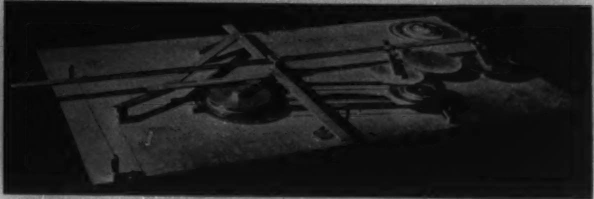


Figure 3. Mechanical device for evaluating θ in the equation $\sin\theta + X\sin(k\theta + \phi) = Y$

there is no practicable analytical method for solving the transcendental equations 6 and 10. Graphical methods could be used but these are time consuming. A mechanical calculating device has been developed for this purpose which is extremely rapid in operation and is sufficiently accurate for all ordinary engineering purposes. The machine is shown in figure 3. A schematic diagram for purpose of explanation is given in figure 4. The theory of operation is given in appendix II.

V. Charts for Matching Boundary Conditions

Given charts of the functions f_s and f_u for a particular idealized circuit, all information about the behavior of that circuit in producing subharmonics can be obtained by carrying out graphically the operation indicated in equation 12. In order that such charts may present the required information in terms of the smallest possible number of parameters, a per-unit system[2] will be used. The base values for this system are:

Base time = seconds per radian of the impressed sinusoid.

Base angular velocity = 2π times the frequency of the impressed sinusoid.

Base quantity of electricity = circuit capacitance in farads times the maximum value of the impressed sinusoid in volts.

Base flux linkages = maximum value of the impressed sinusoid in volts multiplied by base time.

To effect a further simplification in notation, let $1/\sqrt{LC}$ be replaced by ω, then in the above unit system equations 5, 6, 9, and 10 become

$$Q_{k+1} = \left(Q_k + \frac{\omega^2 \sin\beta_k}{1-\omega^2}\right)\cos\omega t_k + \frac{\omega\cos\beta_k}{1-\omega^2}\sin\omega t_k - \frac{\omega^2}{1-\omega^2}\sin(t_k + \beta_k) \quad (13)$$

$$0 = \cos\beta_k \cos\omega t_k - \omega\left(\frac{1-\omega^2}{\omega} Q_k + \sin\beta_k\right)\sin\omega t_k - \cos(t_k + \beta_k) \quad (14)$$

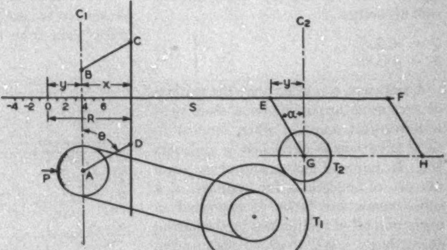
$$Q_{m+1} = Q_m \quad (15)$$

$$\cos\beta_{m+1} + Q_m\beta_{m+1} = \cos\beta_m + Q_m\beta_m \pm 2\psi_s, 0 \quad (16)$$

From these equations it is evident that the function f_s depends upon the single parameter ω and that the function f_u depends upon the single parameter ψ_s. The parameter ω, the per-unit angular velocity, is the ratio of the "saturated natural frequency" to the impressed frequency. The parameter ψ_s, the per-unit value of flux linkages at the knee of the saturation curve, is the ratio of the reactor voltage at normal frequency when operating at the knee of the curve to the impressed voltage.

Figures 5 and 6 give the functions f_s and f_u respectively. In figure 5, ω has the value $1/2.5 = 0.63$. In figure 6, ψ_s has the value 1.15. In figure 5, the contours are plotted in rectangular co-ordinates to give greater accuracy in reading β when Q is small than could be obtained in a polar plot; this method of plotting also allows the physical interpretation to be stressed by making a distinction between negative modulus (negative charge) and a phase shift to 180 degrees. In figure 6 β_{m+1} versus β_m is shown for a range of values of Q_m. Since $Q_{m+1} = Q_m$, these curves completely determine the function f_u.

Figure 4. Mechanical device for evaluating θ in the equation $\sin\theta + X\sin(k\theta + \phi) = Y$



The curves of β_{m+1} versus β_m have discontinuities so that they appear in three or more sheets. Of these sheets all except those inside the region marked out in the heavy shield-shaped area have positive slope with β_m. All points on curves with positive slopes represent transitions from $+\psi_s$ to $-\psi_s$ or vice versa. Points on curves having negative slopes (those within the shield-shaped area) represent a return to $\pm\psi_s$ after having left it without crossing over to the opposite saturated region.

VI. Stability of Subharmonic Oscillations

If, after a certain sequence of transitions from region to region, the boundary conditions for a given subharmonic oscillation are recurrent as expressed by equation 12, then in the succeeding interval of time the same sequence of transitions from region to region should occur. Suppose that in the course of such oscillation some small disturbing influence should occur. Mathematically this may be expressed by replacing Q by $Q + \Delta Q$ and β by $\beta + \Delta\beta$. Then after a complete period we have

$$Q + \Delta_1 Q\underline{/\beta + \Delta_1\beta} = f_s f_u \cdots f_s f_u f_s f_u \left(Q + \Delta Q\underline{/\beta + \Delta\beta}\right) \quad (17)$$

If the increments $\Delta_1 Q$ and $\Delta_1\beta$ are greater than the increments ΔQ and $\Delta\beta$ the effect of the disturbing influence will grow with each successive excursion over the sequence of values constituting a period, until ultimately the periodic nature of the phenomenon is destroyed. If, however, $\Delta_1 Q$ and $\Delta_1\beta$ are smaller than the disturbances producing them the effect diminishes from period to period; in this case the oscillation is stable.

The condition for stability is the analytical equivalent of the condition for convergence of the successive approximation solution of equation 12. This equation

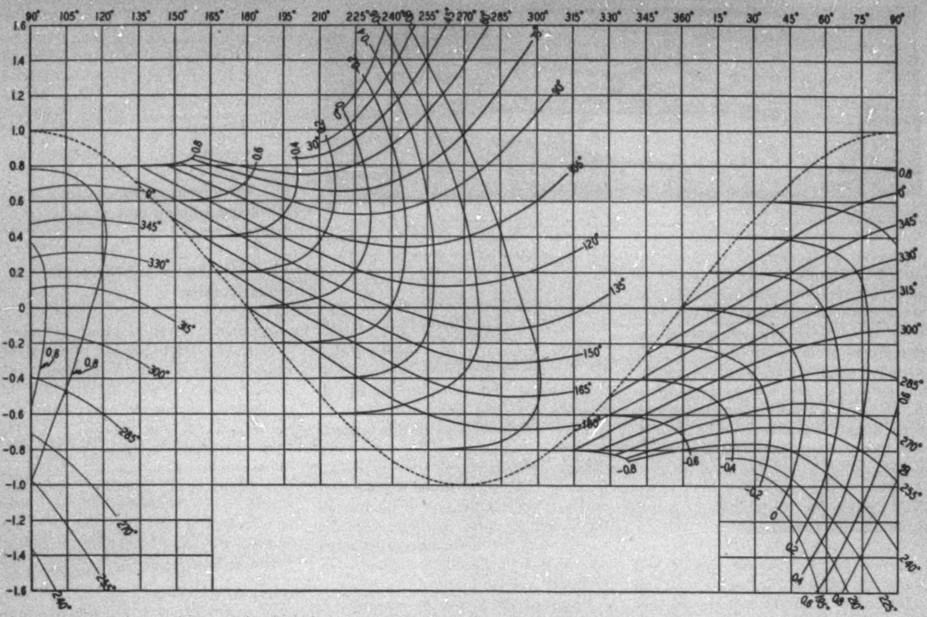


Figure 5. Chart of the function $f_k(Q_k)$

Contours give loci of Q_{k+1}/β_{k+1} for Q_k = constant and β_k = constant ($LC = 2.5$)

represents a functional relationship which must be satisfied by a certain number-pair (Q,β). The relationship could equally well be written

$$\left.\begin{aligned} Q &= u(Q,\beta) \\ \beta &= v(Q,\beta) \end{aligned}\right\} \quad (18)$$

A sufficient condition that the method of successive approximations shall yield a convergent solution when applied to these equations is developed in appendix III. In terms of charge and phase angle the set of conditions for stability of a subharmonic oscillation is expressed in terms of a set of restrictions on the partial derivatives $\partial Q_{k+1}/\partial Q_k$, $\partial Q_{k+1}/\partial \beta_k$, $\partial \beta_{k+1}/\partial Q_k$, $\partial \beta_{k+1}/\partial \beta_k$, $\partial \beta_{m+1}/\partial Q_m$, $\partial \beta_{m+1}/\partial \beta_m$.

The labor of carrying out a comprehensive analytical investigation of the behavior of these partial derivatives would be prohibitive. They can be evaluated in any particular case by graphical methods, however, with relatively little difficulty.

The solid curves of figure 7 show a differential analyzer solution for the charge and flux linkage* in a circuit in which $\omega = 0.63$ and $\psi_s = 1.15$.

After the first few cycles the charge seems to be essentially periodic. The wave form from cycle to cycle changes slightly but the general nature of the oscillation is the same. Although the current is not shown it is evident that there are two current pulses of the same sign and approximately equal magnitude for each half cycle of the subharmonic oscillation. This wave form is characteristic of the oscillations commonly encountered in actual electric circuits. The dotted curve shows values of charge

Table I

	Point Number							
	1	2	3	4	5	6	7	8
Q_k		0.15		−0.81		−0.08		0.94
β_k		246°		132°		51°		302°
Q_m	0.15		−0.81		−0.08		0.94	
β_m	90°		58°		298°		232°	
$\frac{\partial Q_{k+1}}{\partial Q_k}$		−0.4		+0.3		−0.6		−0.43
$\frac{\partial Q_{k+1}}{\partial \beta_k}$		+0.7		−0.92		−0.53		+1.07
$\frac{\partial \beta_{k+1}}{\partial Q_k}$		+1.13		−1.82		−1.00		+1.5
$\frac{\partial \beta_{k+1}}{\partial \beta_k}$		+0.3		+0.32		+0.26		+0.6
$\frac{\partial Q_{m+1}}{\partial Q_m}$	+1.0		+1.0		+1.0		+1.0	
$\frac{\partial Q_{m+1}}{\partial \beta_m}$	0		0		0		0	
$\frac{\partial \beta_{m+1}}{\partial Q_m}$	−2.3		+1.05		+3.14		−0.42	
$\frac{\partial \beta_{m+1}}{\partial \beta_m}$	−1.0		+1.1		−1.0		+0.8	

---

*The flat tops of the flux linkage curve are due to the fact that in the analyzer setup the saturated portion of the ψ versus i curve was drawn parallel with the axis, the ratio of ψ to i in this region being maintained by means of gears. The curve therefore represents flux linkage only for values of ψ less than ψ_s; it is included for convenience in determining phase relationships.

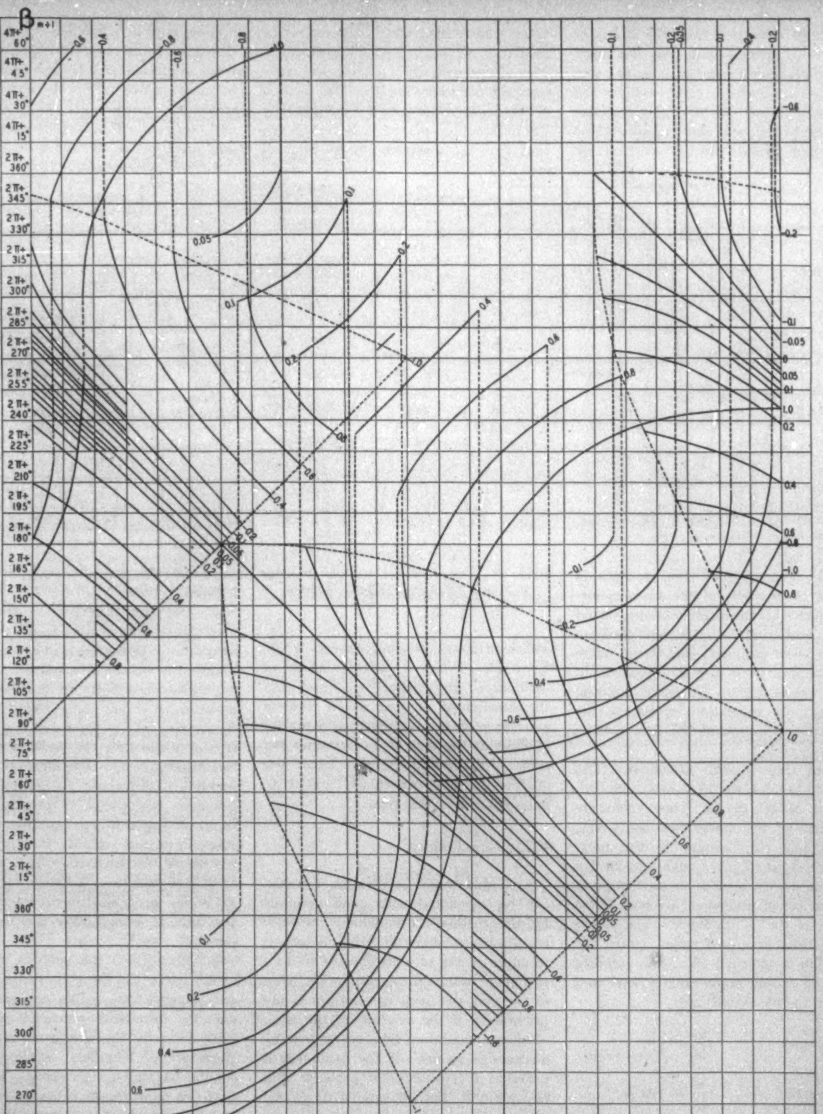


Figure 6. Chart for the function $f_u(Q_m)$

The contours shown are curves of β_{m+1} versus β_m for values of Q_m

and angle calculated from the charts of f_s and f_u, starting with the boundary conditions given by the analyzer at point 1. The two methods check well for the first period after this point, less well for the next period, and poorly for the third succeeding period. If the criterion for stability were satisfied the two methods should check well; if the phenomenon were unstable the result obtained would be expected, that is, the less accurate method (the graphical one) would cause the instability to become apparent in fewer periods than the more accurate method. A tabulation of the partial derivatives throughout the first cycle is shown in table I.

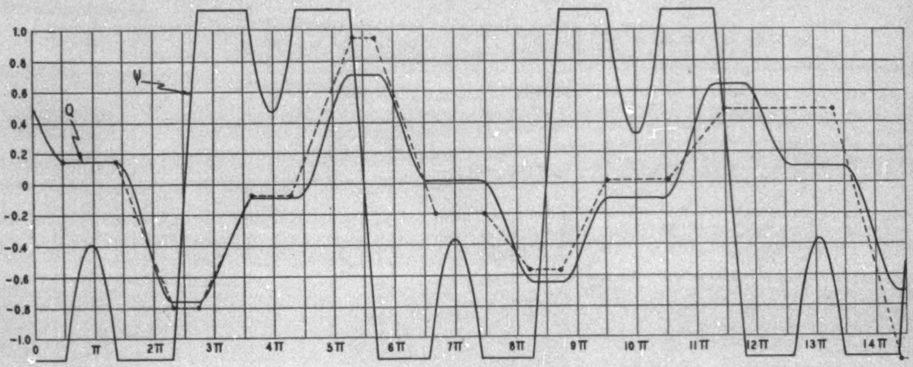


Figure 7. Comparison of graphical calculation with differential analyzer solution

From these partial derivatives it is possible to calculate the values of $\partial u/\partial Q$, $\partial u/\partial \beta$, $\partial v/\partial Q$, $\partial v/\partial \beta$. These values are functions of the derivatives $\partial Q_{k+1}/\partial Q_k$, $\partial Q_{k+1}/\partial \beta_k$, etc., similar to the polynomials A, B, C, D in equations 29 if n of equations 29 is made to correspond to the number of transitions involved in one period of the subharmonic. The values calculated for a half-period (since the two half-periods are alike the stability criterion should apply equally well to a half or a whole period) are:

$$\frac{\partial u}{\partial Q} = 1.56 \qquad \frac{\partial v}{\partial Q} = 1.67$$

$$\frac{\partial u}{\partial \beta} = 0.15 \qquad \frac{\partial v}{\partial \beta} = 0.93$$

It is obvious that the *sufficient condition for stability* is violated; note that this condition is not *necessary*. A consideration of the polynomials A, B, C, D shows that a *sufficient* condition for *instability* is that all partial derivatives have the same sign and that at least one of the derivatives $\partial u/\partial Q$, $\partial v/\partial \beta$ be in absolute value greater than unity. Therefore the oscillation shown in figure 7 is unstable. This agrees with the fact that the wave form calculated by the graphical method of this paper departs from that given by the differential analyzer. It is believed that had the analyzer record been of sufficient duration the charge wave would have drifted into a different mode of oscillation. Experience has shown that the duration of analyzer record required to accomplish this is quite great (a matter of days at the rate of five minutes per cycle of impressed voltage) hence the analyzer is not particularly suited to investigations of this type.

VII. Conclusions

1. Subharmonic oscillations, if stable, can be calculated with good accuracy by the method of matching boundary conditions providing the circuit is such as to admit of the idealizing assumptions 1 to 4 given in the introduction. The labor of carrying out such calculations is not prohibitive if the solution of the transcendental equations involved is done by mechanical means. If the oscillation is unstable it does not seem probable that any analytic method can be developed which will reproduce experimentally observed wave forms.

2. The theory developed in appendix III provides a means for investigating the stability of a given mode of subharmonic oscillation. The application of criteria arising from this theory to specific examples leads to the belief that stable subharmonic oscillations are rare. This opinion may be colored by the fact that throughout this analysis resistance has been neglected. Whether any given harmonic which fulfills the condition of recurrent boundary conditions is stable and therefore will be sustained is a question which probably cannot be answered completely by any analysis which neglects dissipation.

3. The effect of resistance on stability is of greatest importance in the region of saturation. It is shown in appendix IV that a resistance of sufficient size to damp out the oscillation due to its effect in the unsaturated region alone, would so limit the current in the saturated region that it is doubtful that the oscillation would be initiated. The modification of the function f_s to include dissipation should generalize the method of this paper sufficiently to render it capable of determining wave form and stability in any circuit commonly encountered. The addition of exponential cams to vary the radius EG of the mechanical device described in appendix II would make this extension possible.

4. Throughout this analysis the saturation curve has been approximated by two straight lines. This approximation does not introduce appreciable errors in wave form for the first cycle after any given set of boundary conditions. It cannot be stated conclusively however that this approximation has no effect on stability. At least one example can be pointed out (equation 3 of reference 1) in which the stable subharmonic depends upon a particular shape of saturation curve. In this example, however, the two straight lines would not represent a good approximation to the curve and therefore would not be expected to produce the same character of oscillation.

Appendix I

Nature of the Function f.

Consider the equation 4. If, at $t = 0$, di/dt is positive, we have a condition corresponding to entrance into the *positive* saturation region. If, on the other hand, di/dt is negative, the condition corresponds to that which obtains at entrance into the *negative* saturated region.

If $di/dt = 0$, we have the limiting condition at which a saturated value $\pm\psi_s$ is just reached but not entered so that no change in charge results. From equation 1 it is evident that for $di/dt = 0$ when $t = 0$ the following relation holds:

$$Q_k = CE \sin \beta_k \tag{19}$$

Since this represents a condition of contact with a saturated region, but zero time of operation in the saturated region, the corresponding values of Q_{k+1} and β_{k+1} are

$$Q_{k+1} = Q_k$$
$$\beta_{k+1} = \beta_k$$

hence

$$Q_{k+1} = CE \sin \beta_{k+1} \tag{20}$$

that is, the circle in the $\boldsymbol{Q_k}$ plane given by equation 19 transforms into the circle in the $\boldsymbol{Q_{k+1}}$ plane given by equation 20. A point $\boldsymbol{Q_k}$ which satisfies (19) represents a point of contact with the positive saturated region when the curve of current versus time is concave down. This is the case providing d^2i/dt^2 is negative or, from equation 19, providing $\cos \beta_k < 0$. A point representing such a contact with the positive saturated region may also be regarded as a limiting condition of operation in the negative saturated region. In this case it represents the angle which for a given charge Q_k produces the longest possible excursion in the negative saturated region.

All contours in the $\boldsymbol{Q_k}$ plane crossing the contour $\boldsymbol{Q_k} = CE \sin \beta_k$ yield contours in the $\boldsymbol{Q_{k+1}}$ plane which are discontinuous at the contour $\boldsymbol{Q_{k+1}}$ at values of β_{k+1} in the range 90 degrees $< \beta_{k+1} <$ 270 degrees correspond to operation in the positive saturated region. Those contours terminating on that contour at values of β_{k+1} in the range -90 degrees $< \beta_{k+1} <$ 90 degrees correspond to operation in the negative saturated region. Since the circle $Q = CE \sin \beta$ is traced over twice as β varies through 360 degrees all points have dual physical interpretations.

The above is illustrated in figure 2. In this figure three contours in the $\boldsymbol{Q_k}$ plane, the circle $Q_k = CE \sin \beta_k$, the circle $Q_k = 2$, the straight line $\beta_k = 120$ degrees for $4.32 > Q_k > -\infty$, are shown. The constants of the circuit are $L = 0.5$, $C = 5.0$, and $E = 1.0$.

Appendix II

Mechanical Solution of a Trigonometric Equation

Referring to figure 4, *ABCD* and *EFGH* are parallelograms with pivots at each corner. θ is the angle through which the arms *BC* and *AD* have been rotated in a clockwise direction from the center line C_1. α is the angle through which the arms *EG* and *FH* have been rotated in a counterclockwise direction from the center line C_2. It is evident from the geometry that

$$x = \overline{BC} \sin \theta \tag{21}$$

$$y = \overline{EG} \sin \alpha \tag{22}$$

S is a scale carried on *EF* extended, the zero of the scale being located at a distance from *E* equal to the distance between the center lines C_1 and C_2. Since the scale moves to the left and the bar *CD* moves to the right, the reading *R* of the bar on the scale is the sum of the displacements x and y.

$$R = x + y = \overline{BC} \sin \theta + \overline{EG} \sin \alpha \tag{23}$$

The protractor *P* which is used to measure θ is belted to a pulley of equal diameter to which is pinned a gear having T_1 teeth. This gear meshes with a gear having T_2 teeth which is attached to the arm *EG*. It is evident that α could be set equal to zero and θ assigned any arbitrary value β before the gears are meshed. Then we have

$$\alpha = \frac{T_1}{T_2} (\theta - \beta) \tag{24}$$

or substituting in (23)

$$\sin \theta + \frac{\overline{EG}}{\overline{BC}} \sin\left(\frac{T_1}{T_2}\theta - \frac{T_1}{T_2}\beta\right) = \frac{R}{\overline{BC}} \tag{25}$$

$\overline{BC}$ is 10 centimeters, $\overline{EG}$ is adjustable on a centimeter scale, *R* is read on a centimeter scale, and the gear ratio $T_1{:}T_2$ is adjustable. Hence we may set up the equation

$$\sin \theta + X \sin (k\theta + \phi) = Y \tag{26}$$

by first setting *X*, *k*, and ϕ, and then moving the mechanism as a whole until *Y* is read on the scale S. The corresponding reading of the protractor is θ.

Appendix III

On the Solution of a Pair of Equations by the Method of Successive Approximations

Given the two equations

$$\left.\begin{aligned} x &= u(x,y) \\ y &= v(x,y) \end{aligned}\right\} \tag{27}$$

two sequences of numbers $\alpha_0, \alpha_1, \alpha_2 \ldots \alpha_n$ and $\beta_0, \beta_1, \beta_2 \ldots \beta_n$ may be defined by the scheme

$$\begin{aligned} \alpha_1 &= u(\alpha_0, \beta_0) \\ \beta_1 &= v(\alpha_0, \beta_0) \\ \alpha_2 &= u(\alpha_1, \beta_1) \\ \beta_2 &= v(\alpha_1, \beta_1) \\ &\cdots\cdots \\ &\cdots\cdots \\ \alpha_n &= u(\alpha_{n-1}, \beta_{n-1}) \\ \beta_n &= v(\alpha_{n-1}, \beta_{n-1}) \end{aligned}$$

By application of the mean value theorem we have:

$$\alpha_2 - \alpha_1 = u(\alpha_1, \beta_1) - u(\alpha_0, \beta_0) = \left.\frac{\partial u}{\partial x}\right]_{a_1,b_1} (\alpha_1 - \alpha_0) + \left.\frac{\partial u}{\partial y}\right]_{a_1,b_1} (\beta_1 - \beta_0)$$

$$\alpha_3 - \alpha_2 = u(\alpha_2, \beta_2) - u(\alpha_1, \beta_1) = \left.\frac{\partial u}{\partial x}\right]_{a_2,b_2} (\alpha_2 - \alpha_1) + \left.\frac{\partial u}{\partial y}\right]_{a_2,b_2} (\beta_2 - \beta_1)$$

. . . .

. . . .

$$\alpha_0 < a_1 < \alpha_1 \qquad \alpha_1 < a_2 < \alpha_2 \qquad \ldots\ldots$$
$$\beta_0 < b_1 < \beta_1 \qquad \beta_1 < b_2 < \beta_2 \qquad \ldots\ldots$$

$$\beta_2 - \beta_1 = v(\alpha_1, \beta_1) - v(\alpha_0, \beta_0) = \left.\frac{\partial v}{\partial x}\right]_{a_1^1,b_1^1} (\alpha_1 - \alpha_0) + \left.\frac{\partial v}{\partial y}\right]_{a_1^1,b_1^1} (\beta_1 - \beta_0)$$

$$\beta_3 - \beta_2 = v(\alpha_2, \beta_2) - v(\alpha_1, \beta_1) = \left.\frac{\partial v}{\partial x}\right]_{a_2^1,b_2^1} (\alpha_2 - \alpha_1) + \left.\frac{\partial v}{\partial y}\right]_{a_2^1,b_2^1} (\beta_2 - \beta_1)$$

. . . .

. . . .

$$\alpha_0 < a_1^1 < \alpha_1 \qquad \alpha_1 < a_2^1 < \alpha_2 \qquad \ldots\ldots$$
$$\beta_0 < b_1^1 < \beta_1 \qquad \beta_1 < b_2^1 < \beta_2 \qquad \ldots\ldots$$

Let us suppose that the region under consideration is sufficiently small that partial derivative may be assumed to be constant.

$$\frac{\partial u}{\partial x} = U_x, \quad \frac{\partial u}{\partial y} = U_y, \quad \frac{\partial v}{\partial x} = V_x, \quad \frac{\partial v}{\partial y} = V_y \tag{28}$$

From the above it is possible to express $(\alpha_n - \alpha_{n-1})$ and $(\beta_n - \beta_{n-1})$ in terms of $(\alpha_1 - \alpha_0)$ and $(\beta_1 - \beta_0)$, for example

$$(\alpha_4 - \alpha_3) = (\alpha_1 - \alpha_0)(U_x^3 + 2U_xU_yV_x + U_yV_xV_y) + (\beta_1 - \beta_0)(U_x^2U_y + U_xU_yV_y + U_y^2V_x + U_yV_y^2)$$

$$(\beta_4 - \beta_3) = (\alpha_1 - \alpha_0)(U_x^2V_x + U_yV_x^2 + U_xV_xV_y + V_xV_y^2) + (\beta_1 - \beta_0)(U_xU_yV_x + 2U_yV_xV_y + V_y^3)$$

In general we have:

$$\begin{aligned} (\alpha_n - \alpha_{n-1}) &= (\alpha_1 - \alpha_0)A + (\beta_1 - \beta_0)B \\ (\beta_n - \beta_{n-1}) &= (\alpha_1 - \alpha_0)C + (\beta_1 - \beta_0)D \end{aligned} \tag{29}$$

in which *A*, *B*, *C*, and *D* are all homogeneous polynomials in U_x, U_y, V_x, V_y, each of degree $(n - 1)$ and each containing 2^{n-2} terms. Let the greatest term in any of these polynomials be

$$U_x^a\, U_y^b\, V_x^c\, V_y^d = M^{n-1} \quad (a + b + c + d = n - 1) \tag{30}$$

then we have

$$\alpha_n - \alpha_{n-1} < \frac{(\alpha_1 - \alpha_0) + (\beta_1 - \beta_0)}{2}(2M)^{n-1}$$

$$\beta_n - \beta_{n-1} < \frac{(\alpha_1 - \alpha_0) + (\beta_1 - \beta_0)}{2}(2M)^{n-1}$$

$$\left.\begin{aligned} \lim_{n \to \infty} \alpha_n - \alpha_{n-1} &= 0 \\ \lim_{n \to \infty} \beta_n - \beta_{n-1} &= 0 \end{aligned}\right\} M < \frac{1}{2} \tag{31}$$

Hence the sequence $\alpha_0, \alpha_1 \ldots \alpha_n$ approaches a limit and the sequence $\beta_0, \beta_1 \ldots \beta_n$ likewise approaches a limit providing $M < \frac{1}{2}$. Let the limits be respectively X and Y. Then

$$X = u(X,Y)$$
$$Y = v(X,Y)$$

It follows therefore that, assuming any arbitrary initial values α_0, β_0, the equations 27 may be solved by successive approximations providing

$$\left|\frac{\partial u}{\partial x}\right|^a \cdot \left|\frac{\partial u}{\partial y}\right|^b \cdot \left|\frac{\partial v}{\partial x}\right|^c \cdot \left|\frac{\partial v}{\partial y}\right|^d \leqq M^{a+b+c+d},\ M < \frac{1}{2} \qquad (32)$$

for all a, b, c, d.

Clearly this condition is satisfied if

$$\left|\frac{\partial u}{\partial x}\right| < M,\ \left|\frac{\partial u}{\partial y}\right| < M,\ \left|\frac{\partial v}{\partial x}\right| < M,\ \left|\frac{\partial v}{\partial y}\right| < M \qquad (33)$$

Note that U_x and V_y are dimensionless and are therefore independent of the units in which the quantities x and y are expressed, whereas U_y and V_x are dependent upon the units. An investigation of the polynomials A, B, C, D shows that in any term in which either U_y or V_x occurs the degree of the term in V_x is equal to the degree in U_y or to that degree plus or minus one. Hence in the application of the theorem to physical problems in which scale factors enter, the criterion can be rendered independent of units by requiring that

$$\left|\frac{\partial u}{\partial y}\right| \cdot \left|\frac{\partial v}{\partial x}\right| < M^2 \qquad (34)$$

If it is desired to apply the criterion in the form in which it appears in the inequalities (33), it is necessary first to put the physical equations in such form that the variables themselves are dimensionless.

Appendix IV

Effect of Resistance on Stability

With an initial charge on the capacitor or with a switching angle such as to swing ψ beyond saturation the phenomenon will always start. Since in the unsaturated region the charge is trapped, the flux linkages will have a component approximately equal to $-v_ct$. In order for the phenomenon to stop it would be necessary for a current pulse completely to eliminate the charge on the capacitor and at the same time for the angle of emergence from the saturated region to correspond to a voltage peak, or for the attenuation due to resistance in the unsaturated region to be such as to reduce ψ to a size less in absolute value than ψ_s.

Consider the possibility of the latter case. Referring to figure 5 in reference 1 it is seen that at the instant T_{k-1}, the charge is $-Q_k$. If instead of assuming infinite inductance along the unsaturated portion of the characteristic, an inductance L is assumed, we have a current at the instant T_{k-1} equal to $-\psi_s/L$. The equation which holds for the succeeding interval of time is

$$L\frac{d^2q}{dt^2} + r\frac{dq}{dt} + \frac{1}{c}q = E \sin t \qquad (35)$$

This equation is subject to the initial conditions

$$t = T_{k-1} = 2r\pi + \gamma \qquad q = -Q_k$$
$$i = -\frac{\psi_s}{L}$$

Let us change the origin of time to the instant of leaving the negative saturated region. Then the electromotive force is $E \sin (t + \gamma)$ and $t = 0$ initially. Since the inductance L is very large, the *steady-state current* may be taken as $(-E/L) \cos t$, hence the total charge and current are

$$q = A\epsilon^{\alpha t} \sin (\omega t + \theta) - \frac{E}{L} \sin (t + \gamma) \qquad (36)$$

$$i = A\epsilon^{\alpha t} \sin (\omega t + \theta) +$$
$$\omega A\epsilon^{\alpha t} \cos (\omega t + \theta) - \frac{E}{L} \cos (t + \gamma) \qquad (37)$$

where

$$\alpha = -\frac{r}{2L}$$

$$\omega = \sqrt{\frac{1}{LC} - \frac{r^2}{4L^2}} = \frac{1}{\sqrt{LC}} \text{ approximately}$$
$$\text{since } \frac{r^2}{4L^2} << \frac{1}{LC}$$

We have the boundary conditions

$$t = 0 \quad q = -Q \quad i = -\frac{\psi_s}{L} \qquad (38)$$

which when substituted in (36) and (37) yield

$$\theta = \sin^{-1}\frac{E \sin \gamma - LQ}{LA} \qquad (39)$$

$$A = \sqrt{\frac{C}{L}} \times$$
$$\sqrt{E^2 - 2E(\psi_s \cos \gamma + LQ \sin \gamma) + \psi_s^2 + L^2Q^2} \qquad (40)$$

Equation 40 is subject to the condition

$$\frac{r}{L}(E \cos \gamma - \psi_s)(E \sin \gamma - LQ) \rightarrow 0$$

which is justifiable because in normal circuits

$$L \gtreqqless 40 \quad \psi_s < 1.5 \quad E \sin \gamma \lesseqqgtr 1 \quad E \cos \gamma \lesseqqgtr 1$$

For the subharmonic oscillation to be damped out $|\psi|$ must become and remain less than ψ_s.

Since $\psi = Li$ we have

$$\psi = LA\epsilon^{\alpha t} [(\alpha \sin \theta + \omega \cos \theta) \cos \omega t +$$
$$(\alpha \cos \theta - \omega \sin \theta) \sin \omega t] -$$
$$E \cos (t + \gamma) \qquad (41)$$

The denominator in equation 39 is a large quantity; let us neglect $\sin \theta$ to a first approximation, then

$$\psi = \sqrt{LC} \times$$
$$\sqrt{E^2 - 2E(\psi_s \cos \gamma + LQ \sin \gamma) + \psi_s^2 + L^2Q^2} \times$$
$$\epsilon^{-\frac{rT}{2L}}\left[-\frac{r}{2L} \sin \omega t + \frac{1}{\sqrt{LC}} \cos \omega t\right] -$$
$$E \cos (t + \gamma) \qquad (42)$$

It is evident that for subharmonics having long periods the resistance has greater effect in the unsaturated region than for oscillations of short periods. Let us calculate the value of resistance which would make impossible all oscillations having periods greater than 10π. The following numerical values represent a typical circuit:

$t = 3\pi$ (approximately) $\quad C = 5 \quad L = 40$
$\cos (t + \gamma) = -1$(approximately) $\quad Q = 1$
$\psi_s = 1.15$

These yield the transcendental equation

$$1.15 = 209\epsilon^{-0.117r}[-0.0077r + 0.055] + 1 \qquad (43)$$

Solving (43), we have $r = 7.1$, a value so great that the oscillation would be eliminated due to attenuation in the current flow interval long before this limit were reached. This suggests that for oscillations of comparatively short period the damping in the saturated region is far more important than that in the unsaturated region. Hence the inclusion of the effect of resistance in the charts for the function $f_s(Q_k)$ might lead to values of partial derivatives which fulfill stability criteria.

A small resistance would eliminate very long periods due to damping in the unsaturated region and very short periods due to reduction of the current pulse during operation in the saturated region. It appears that as the resistance increases there may be one intermediate harmonic which would be last eliminated, the subharmonics on either side being successively cut off. This may mean that there is a most stable mode of oscillation for a given circuit, and that, although theoretical considerations thus far presented indicate infinitely many steady states, there is one subharmonic oscillation most likely to be produced regardless of varying boundary conditions.

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The Generalized Solution for the Critical Conditions of the Ferroresonant Parallel Circuit

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Synopsis: In a recent paper "Similitude of Critical Conditions in Ferroresonant Circuits,"[24] a generalized solution for the critical conditions of the series circuit was given. The same type of generalized treatment when applied to the parallel circuit yields a number of interesting conclusions to supplement those found for the series circuit.

Characteristics of the Parallel Circuit

FIGURE 1 represents the typical volt-ampere relation of the parallel circuit. Unlike the series circuit with its voltage-sensitive characteristics, the parallel circuit is known to be current sensitive[12,22] in the critical region.

It is noted here that the critical current is greatly dependent on the value of X_c used, and as in the series circuit, this current increases with a decrease of X_c. Also, the critical voltage increases with a decrease of X_c. The effect of varying the resistance is most noticeable in the critical region, the reduction of this resistance increasing the current dip found in such circuits.

Generalized Treatment of the Parallel Circuit

The circuit referred to in this investigation is shown in figure 2. The critical conditions are defined by the following equation:

$$\frac{di_0}{dE} = 0 \tag{1}$$

where i_0 represents the total line current. Referring again to figure 1, it should be apparent that with a resistance less than the critical value, the above relation is satisfied by two values of current and voltage, while with a critical resistance in the circuit these two values of current and voltage approach a single value.

Rewriting equation 1,

$$\frac{di_0}{dE} = \frac{di_0}{di_L} \cdot \frac{di_L}{dE} = 0 \tag{2}$$

Since di_L/dE can never become zero, $di_0/di_L = 0$ will satisfy the above relation. Generalizing, the critical points will be defined by the following equation:

$$\frac{d\left(\frac{ni_0}{l}\right)}{d\left(\frac{ni_L}{l}\right)} = 0 \tag{3}$$

Table I. Data for Reactor 5

$n = 800$ $\quad (nA) = 760$

$A = 0.95$ square inch $\quad \left(\frac{n^2A}{l}\right) = 83{,}400$

$l = 7.3$ inches $\quad \left(\frac{n}{l}\right) = 109.7$

Standard Circuit ($R_1 = 0$; $R_2 = 104$ ohms) E	Standard Circuit ($R_1 = 0$; $R_2 = 104$ ohms) I_0	New Circuit ($R_1 = 104$ ohms; $R_2 = 0$) E	New Circuit ($R_1 = 104$ ohms; $R_2 = 0$) I_0
63	0.20	58	0.20
94	0.30	87	0.30
120	0.35	106	0.35
142	0.40	124	0.40
155	0.41	160	0.45
185	0.415	182	0.46
196	0.415	200	0.46
205	0.42	210	0.47
214	0.45	229	0.50
220	0.50	255	0.60
229	0.60		

Critical stable values

E	= 185	E	= 190
I_0	= 0.415	I_0	= 0.46
I_L	= 0.347	I_L	= 0.345
R	= 104	R	= 104
X_c	= 268	X_c	= 268
$\left(\frac{E}{nA}\right)$	= 0.243	$\left(\frac{E}{nA}\right)$	= 0.250
$\left(\frac{ni_0}{l}\right)$	= 45.5	$\left(\frac{ni_0}{l}\right)$	= 50.5
$\left(\frac{ni_L}{l}\right)$	= 38.0	$\left(\frac{ni_L}{l}\right)$	= 37.9
$\left(\frac{R}{\frac{n^2A}{l}}\right)$	= 0.00125	$\left(\frac{R}{\frac{n^2A}{l}}\right)$	= 0.00125
$\left(\frac{X_c}{\frac{n^2A}{l}}\right)$	= 0.00321	$\left(\frac{X_c}{\frac{n^2A}{l}}\right)$	= 0.00321

It is now necessary to express ni_0/l in terms of ni_L/l. Using the same notation as that of the series circuit, the reactance and the apparent resistance of the reactor can be expressed as follows (reference 24, equations 5 and 6):

$$X_L = \frac{E_{LX}}{i_L} = \frac{nA\beta}{i_L} = \left(\frac{n^2A}{l}\right)\frac{\beta}{\left(\frac{ni_L}{l}\right)} \tag{4}$$

$$R_L = \frac{E_{LR}}{i_L} = \frac{nA\alpha}{i_L} = \left(\frac{n^2A}{l}\right)\frac{\alpha}{\left(\frac{ni_L}{l}\right)} \tag{5}$$

where:

E_{LX} = reactive component of the reactor voltage
E_{LR} = in-phase component of the reactor voltage
n = number of turns on the reactor
A = cross-section area of the magnetic path
l = length of the magnetic path
β = $4\gamma f B_{\max} \times 10^{-8}$ = a function of (ni_L/l)
γ = form factor
α = $\rho\frac{\left(\frac{W}{\#}\right)}{K\left(\frac{ni_L}{l}\right)}$ = a function of (ni_L/l)
$\left(\frac{W}{\#}\right)$ = watts per pound of iron
ρ = $\left(\frac{\#}{Al}\right)$ = density of iron used
K = i_1/i_L = ratio of fundamental to effective current

Since

$$i_0 = i_L \cdot \frac{Z_1 + Z_2}{Z_2} \tag{6}$$

$$\frac{ni_0}{l} = \frac{ni_L}{l} \times \sqrt{\frac{\left[R_1 + R_2 + \left(\frac{n^2A}{l}\right)\frac{\alpha}{\left(\frac{ni_L}{l}\right)}\right]^2 + \left[\left(\frac{n^2A}{l}\right)\frac{\beta}{\left(\frac{ni_L}{l}\right)} - X_c\right]^2}{R_2^2 + X_c^2}}$$

$$\frac{ni_0}{l} = \sqrt{\frac{\left[\alpha + \left(\frac{ni_L}{l}\right)\left(\frac{R_1 + R_2}{\frac{n^2A}{l}}\right)\right]^2 + \left[\beta - \left(\frac{ni_L}{l}\right)\left(\frac{X_c}{\frac{n^2A}{l}}\right)\right]^2}{\left(\frac{R_2}{\frac{n^2A}{l}}\right)^2 + \left(\frac{X_c}{\frac{n^2A}{l}}\right)^2}} \tag{7}$$

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24. For all numbered references, see list at end of paper.

Differentiation and equating it to zero,

$$\frac{d\left(\dfrac{ni_0}{l}\right)}{d\left(\dfrac{ni_L}{l}\right)} = \frac{1}{\sqrt{\left(\dfrac{R_2}{\dfrac{n^2A}{l}}\right)^2 \left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)^2}} \left\{ \frac{\left[\alpha + \left(\dfrac{ni_L}{l}\right)\left(\dfrac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)\right]\left[\dfrac{d\alpha}{d\left(\dfrac{ni_L}{l}\right)} + \left(\dfrac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)\right] + \left[\beta - \left(\dfrac{ni_L}{l}\right)\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)\right]\left[\dfrac{d\beta}{d\left(\dfrac{ni_L}{l}\right)} - \left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)\right]}{\sqrt{\left[\alpha + \left(\dfrac{ni_L}{l}\right)\left(\dfrac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)\right]^2 + \left[\beta - \left(\dfrac{ni_L}{l}\right)\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)\right]^2}} \right\} = 0$$

Therefore,

$$\left\{\alpha + \left(\frac{ni_L}{l}\right)\left(\frac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)\right\}\left\{\frac{d\alpha}{d\left(\dfrac{ni_L}{l}\right)} + \left(\frac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)\right\} = -\left\{\beta - \left(\frac{ni_L}{l}\right)\left(\frac{X_c}{\dfrac{n^2A}{l}}\right)\right\}\left\{\frac{d\beta}{d\left(\dfrac{ni_L}{l}\right)} - \left(\frac{X_c}{\dfrac{n^2A}{l}}\right)\right\} \quad (8)$$

It is interesting to note that equation 8 is essentially identical to equation 9 of the series circuit (see equation 9, reference 24).

The generalized voltage is obtained by the following equation:

$$E^2 = \left\{nA\alpha + \left(\frac{ni_L}{l}\right)\frac{R_1}{\left(\dfrac{n}{l}\right)}\right\}^2 + \{nA\beta\}^2$$

$$\left\{\frac{E}{nA}\right\}^2 = \left\{\alpha + \left(\frac{ni_L}{l}\right)\left(\frac{R_1}{\dfrac{n^2A}{l}}\right)\right\}^2 + \{\beta\}^2 \quad (9)$$

The Principle of Similitude of Parallel Circuits

From equations 7, 8, and 9 a number of conclusions can be drawn. The following apply to the critical stable condition.

1. Comparison of equation 8 with the corresponding equation for the series circuit (equation 9 in reference 24) indicates that the critical stable value of ni_L/l and $\left(\dfrac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)$ are equal to those of the series circuit.

2. From equation 8 it is possible to state that two different circuits with equal values of $\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)$ will have equal values of $\left(\dfrac{R_1+R_2}{\dfrac{n^2A}{l}}\right)$ and the ampere turns per inch of the reactor branch for the critical stable condition will be equal.

3. Since the only resistance term appearing in equation 8 is $\left(\dfrac{R_1 + R_2}{\dfrac{n^2A}{l}}\right)$, as far as the critical value of $\left(\dfrac{ni_L}{l}\right)$ is concerned, it matters not whether the resistance is placed all in one branch or divided between the two branches.

4. When $R_1 = 0$, equations 8 and 9 indicate that the critical stable value of $\left(\dfrac{E}{nA}\right)$ depend only on the value of $\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)$.

5. Using $R_1 = 0$ as a standard parallel circuit, a generalized curve for $\left(\dfrac{E}{nA}\right)$, $\left(\dfrac{R_1+R_2}{\dfrac{n^2A}{l}}\right)$, and $\left(\dfrac{ni_0}{l}\right)$ can be drawn with $\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)$ as the independent variable. This generalized curve for the standard circuit can then be used to calculate the critical stable values of $\left(\dfrac{E}{nA}\right)$ and $\left(\dfrac{ni_0}{l}\right)$ for the case where R_1 is not equal to zero by means of the two equations below.

$$\left(\frac{ni_0}{l}\right)_{\substack{R_1\neq0\\R_2=0}} = \left(\frac{ni_0}{l}\right)_{\substack{R_1=0\\R_2\neq0}} \times \sqrt{\frac{\left(\dfrac{R_2}{\dfrac{n^2A}{l}}\right)^2 + \left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)^2}{\left(\dfrac{X_c}{\dfrac{n^2A}{l}}\right)^2}} \quad (10)$$

$$\left(\frac{E}{nA}\right)^2_{\substack{R_1\neq0\\R_2=0}} = \left(\frac{E}{nA}\right)^2_{\substack{R_1=0\\R_2\neq0}} + \left\{\left(\frac{ni_L}{l}\right)\left(\frac{R_1}{\dfrac{n^2A}{l}}\right)\right\}^2 \quad (11)$$

Equation 10 is obtained directly from equation 7 while equation 11 is obtained from equation 9 by assuming α to be negligible in comparison to β.

Experimental Verification of Derived Conclusions

Critical stable values for parallel circuits were obtained experimentally and tabulated in table II. Reactors 1, 2, and 3 used for this purpose were made from the same grade of iron and are the same reactors used in the previous investigation of the series circuit.

The tabulated values of table II are plotted in figure 3 representing the generalized curves for the standard parallel circuit. For comparative purposes the

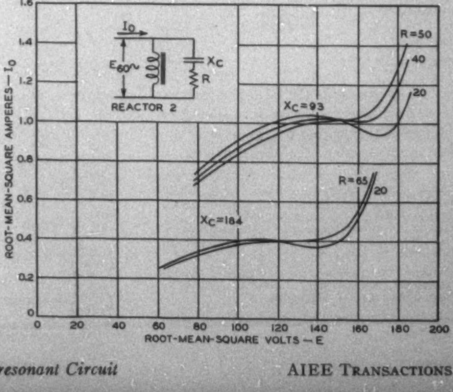


Figure 1. Characteristics of the parallel circuit

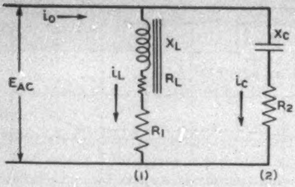


Figure 2. Ferroresonant parallel circuit

values of $\left(\frac{ni_L}{l}\right)$ and $\left(\frac{R_0}{\frac{n^2A}{l}}\right)$ of the series circuit (see reference 24, figure 4) for the same grade of iron are superimposed in dotted lines. It is apparent from these curves that conclusions 1, 2, and 4 are in fairly good agreement.

In order to verify conclusions 3 and 5, the data in table I were taken. The grade of iron used for reactor 5 is unknown; however, this is immaterial for this verification.

It is noted that the critical stable condition is obtained in both cases with $R = 104$ ohms, regardless of whether the resistance is placed in the reactor branch or the capacitor branch. As indicated in (8), the values of $\left(\frac{ni_L}{l}\right)$ are found to be equal for both circuits.

The two terms differing in the two circuits are (ni_0/l) and (E/nA). The following predetermination will illustrate the use of equations 10 and 11 and indicate the validity of conclusion 5.

Table II. Critical Stable Values for the Parallel Circuit

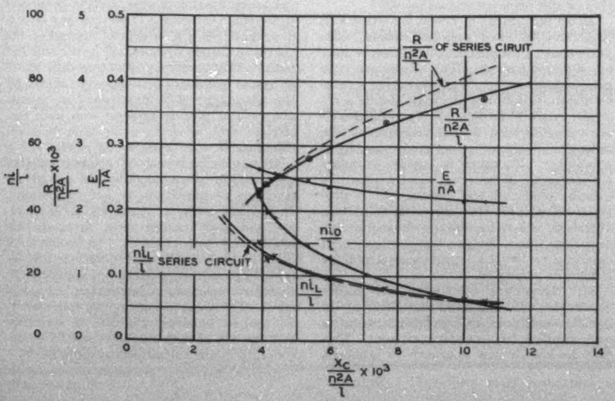
(Tabulated Values—Figure 3)

X_c	E	I_0	I_L	R_2	$\frac{X_c}{\frac{n^2A}{l}}$	$\frac{E}{nA}$	$\frac{ni_0}{l}$	$\frac{ni_L}{l}$	$\frac{R_2}{\frac{n^2A}{l}}$
Reactor 1									
188	335	1.17	0.74	110	0.00411	0.246	39.3	24.8	0.0024
272	320	0.75	0.57		0.00595	0.235	25.1	19.1	
350	310	0.55	0.48	154	0.00765	0.228	18.4	16.1	0.00338
460	290	0.36	0.37		0.0100	0.213	12.1	12.4	
Reactor 2									
93	150	1.02	0.73	49	0.00535	0.248	29.3	21.0	0.00280
184	130	0.40	0.43	65	0.0106	0.215	11.5	12.3	0.00374
Reactor 3									
272	320	0.78	0.53	160	0.0039	0.264	44.8	30.4	0.0023
305	313	0.66	0.46		0.00437	0.259	37.9	26.4	

(See reference 24, table I, for reactor dimension.)

Figure 3. Generalized curves for the parallel circuit

Allegheny dynamo-grade iron



Using the values obtained for the standard circuit and applying equations 10 and 11,

$$\left(\frac{ni_0}{l}\right)_{\substack{R_1=104\\R_2=0}} = 45.5 \times \sqrt{\frac{(0.00125)^2 + (0.00321)^2}{(0.00321)^2}} = 45.5(1.072) = 48.8$$

Experimental value = 50.5

$$\left(\frac{E}{nA}\right)_{\substack{R_1=104\\R_2=0}} = \sqrt{(0.243)^2 + (38.0 \times 0.00125)^2} = \sqrt{0.06125} = 0.248$$

Experimental value = 0.250

The two curves used for this investigation are plotted in figure 4.

Applications of the Parallel Circuit

Although the applications of the parallel circuit are rather limited compared to those of the series circuit, the two examples below are worth mentioning.

The constant-current characteristics of the parallel circuit in the critical region can be utilized in a number of places where it is necessary to maintain a constant voltage in spite of the line-voltage fluctuation. This constant voltage can be obtained by placing a constant impedance in series with the parallel circuit tuned to the critical stable condition. Figure 5 represents the characteristics of such a circuit using a resistance for the series impedance. It is noted here that the line voltage may fluctuate as much as 60 volts without affecting the voltage across the resistor. This resistor may represent an instrument or any other device which must be kept at a constant voltage.

If the resistance R_2 in the parallel circuit is reduced to zero, the negative-slope characteristics of the parallel circuit can be utilized to advantage when applied to a resistance thermometer. The resistance thermometer in this case is placed in series with the parallel circuit. With this negative-slope characteristic, a reduction in the thermometer resistance is accompanied by a reduction in the current through it instead of an increase, thereby producing a greater change in the voltage across the thermometer for a given change in the resistance.

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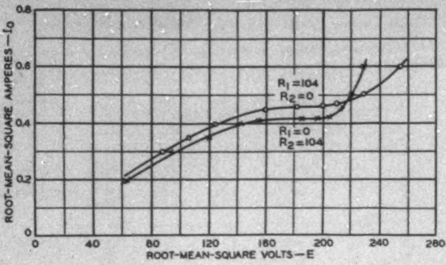

Figure 4. Characteristics of the parallel circuit

Reactor 5; $X_c = 268$

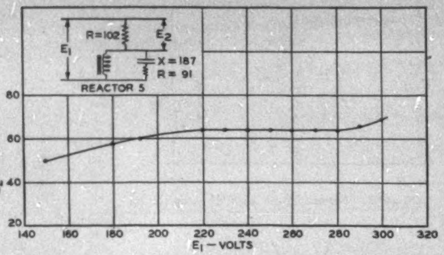

Figure 5. Constant-voltage circuit

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Discussion

Paul H. Odessey (Heyer Products Company, Belleville, N. J.): Mr. Thomson's interpretation of critical conditions through principles of similitude is of noteworthy engineering value. This method of approach happily overcomes the difficulty of dealing with harmonics although the analysis is formulated on the basis of fundamental frequency. The application of similitude principles is, however, dependent upon experimental results and, therefore, constitutes a point-to-point comparison between ferroresonant circuits employing the same grade iron. In wider application, it is essential to obtain by experiment with a standard circuit, a complete set of data covering the entire range of critical values, both stable and unstable before the constants of an unknown circuit can be determined for any condition. This limitation is, however, not objectionable for the results have proved to be uncommonly accurate, although not particularly descriptive of the phenomena in general.

As an implement of study, equation 8 is restrictive in form and application, notwithstanding important conclusions that are deduced from it. This derivative type of equation is, properly speaking, not a solution since it does not explicitly define a relation between the dependent and independent variables, nor does it characterize the influence of circuit parameters on critical conditions. Equation 8 merely expresses a relationship of interdependent parameters existing under critical conditions. A progressive interpretation of critical conditions therefore, is not feasible by means of this equation. Accordingly, the application of equation 8 is limited to problems solvable by similitude principles.

Mr. Thomson's conclusions are highly significant, particularly the identity of critical conditions in corresponding series and parallel ferroresonant circuits. This fact discloses a new approach to problems in critical conditions and embodies an analytical basis for further interpretation of the phenomena.

William T. Thomson: At present there is no exact solution to the ferroresonant problem. Every method developed so far is an approximation, and regardless of the method used recourse must be had to experimental results. For instance, the magnetization curve upon which all previous methods are based must be obtained experimentally and expressed mathematically or used in the graphical form.

The weaknesses of previous methods are twofold: (1) It is necessary to build the reactor first to obtain its characteristics before calculations for its critical points are possible. (2) The treatment is limited to the specific circuit under consideration, from which it is not possible to predict quantitatively the behavior of other circuits.

The type of information which is of greatest value must necessarily be of generalized character where the combined effect of varying the circuit parameters is capable of simple analysis. The generalized treatment with the principle of similitude makes possible this analysis.

This type of analysis is subject to criticism in that similar relations must exist in the two circuits to be compared. However, the generalization of any problem is subject to the same criticism. The accuracy of predetermination will, of course, depend on the degree of similarity obtained in the two circuits. This similarity is not as difficult to obtain as one might preassume, as shown by the agreement of values from the circuits analyzed in the two papers; and with reasonable care, accuracy acceptable for such calculations can be obtained easily.

In conclusion it may be pointed out that the solution of problems by the use of the principle of similitude is not uncommon. In the fields of hydrodynamics, aerodynamics, and heat transfer most problems are handled by such methods. In problems of flood control important conclusions are obtained by building models and applying the similitude principle in developing the model laws. The similitude principle is a powerful tool in handling engineering problems and the use of such methods should be encouraged in the various engineering fields.

Modernization of Switch-House Design

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THERE are many types and characters of switch houses on a power system, and their importance varies through wide limits. Many features which are of great importance and value in one type of installation cannot be justified in others. Probably the most important switching center is that of a generating station located near the center of a load area. In such a station continuity of service is of maximum importance. A complete shutdown of such a plant affects a great number of power users of all classes and the damage can be very great physically, commercially, and politically. This paper will be confined to a discussion of the means which have been used, or are available, to improve the reliability of this type of station.

Reliability of operation involves several factors. The possibility of the occurrence of a fault must be reduced to a minimum, the physical damage produced by a fault must be kept to a minimum, the spread of the fault must be prevented, and as far as possible an interruption of service to any consumer must be prevented.

The problem involves the physical design of the apparatus and its parts, the electrical arrangement of the gear and of the system, auxiliary equipment to cure ailments if they do occur, and the co-ordination of all into one coherent whole.

All electrical failures on a power system are caused by the application of a voltage between conducting materials in excess of the dielectric strength of the insulation between them. This may come about by the appearance of an abnormal voltage on the system whose value exceeds that of the insulation strength deemed necessary, or by the reduction of the strength below the voltages normally expected on the system. Economically sound voltage levels have been established by experience. The general level having been established, it is necessary to co-ordinate several factors to obtain a proper balance between all parts.

Each conductor on a three-phase system has a voltage between it and the other two phase conductors and ground. It is desirable, of course, to eliminate all types of faults but there is a gradation in this desirability. As will be pointed out later, faults involving two or more phases are usually more to be avoided than a single-phase-to-ground fault.

If the established-level insulation strength is obtained and maintained, then a failure is the result of some conducting element or an abnormal voltage entering the structure. The design of the structure must, therefore, prevent all conducting bodies, such as rats and other small animals, from reaching or approaching any live conductor.

Abnormal voltages are possible due to lightning, series resonance, or transient oscillations caused by the abrupt change of system conditions, such as the making or breaking of a circuit. These possibilities must be considered in the station design and steps taken to keep the voltage within reasonable limits.

Even though extreme care is used to obtain good insulation characteristics and to prevent foreign bodies and high voltages, it will be admitted by all that faults will occur. Therefore, the next consideration is to design the gear to minimize the damage which can result. A fault can cause physical damage by burning at the point of fault, by starting faults at other points, and by causing a flow of current in conducting material not designed to handle the flow. Burning at the point of fault is a function of current magnitude, its duration, and the character of the surrounding material. Trouble may be communicated from point to point by solid material thrown by an explosion, by vaporized metal, and by gases, which are the products of combustion. Consideration must then be given to the prevention of explosions and the confining of their effects if this is impossible. Metallic vapors are easily condensed but care must be used that they be confined until condensation is accomplished. Incandescent gases can be carried in a smoke cloud for considerable distances before the screen of smoke weakens and lets oxygen unite with the gas to start combustion. The cloud can deposit on insulators and reduce dielectric strength. Therefore, some attention is required in the design to provide for the cooling and confinement of these gases.

Fault currents have been known to flow in building steel and in control wiring with diastrous results. This flow of current has even caused the short-circuiting of other sound circuits with further damage and a further spread of the fault. So the prevention of this straying of fault current from suitable paths is worthy of considerable study in designing an adequate switchgear.

Care in the design of physical structure can accomplish a great deal in minimizing faults and damage due to a fault but if a fault can seriously disrupt service, then the care taken has been largely wasted. In order to complete the picture it is necessary to examine the electrical connections of the system to see what happens to the system. Provision for isolating the fault must, of course, be provided. This isolation must not cause a serious service interruption and it must be of a nature that system stability is not affected. Therefore, protective equipment and system design must be so co-ordinated that a fault cannot cause a severe system "shake-up" nor directly disconnect any important load.

Physical Structure

There have been many instances where switching stations have grown in capacity far beyond that contemplated in their original design. Such cases demand a serious reconsideration of their basic design and layout in order to accomplish objectives which become more clearly defined as a result of such growth.

The program for modernization of an existing switching structure is most commonly based on a desire to obtain one or more of the following:

1. Increased interrupting ability of oil circuit breakers.
2. Faster operation of oil circuit breakers.
3. Reduction in volume of oil.
4. Additional safety to operators.
5. Higher insulation level and phase segregation.
6. Greater reliability.

Interrupting Ability

Overstressed circuit breakers are commonly the first problem to be solved, either by substitution of entirely new breakers or, if of reasonably recent vintage, by modernization. Fortunately, new high-capacity breakers affording higher speed of operation, higher insulation level, and greater reliability are now available, requiring little if any more space

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than that occupied by old breakers to be replaced. In many cases these may be installed in cells already available.

Methods of modernizing oil circuit breakers have been widely discussed and will not be repeated here. The test of time and experience has proved that the proper application of arc control devices to most old-style breakers will result in greatly improved operation. In general, such changes increase interrupting ability, and because of shortened arcing time, greatly reduced contact burning and oil deterioration for any given service. This, of course, permits lengthening the period between necessary overhauls with a resultant decrease in maintenance expense. In most cases such changes can be made without altering the size of the structures in which the breakers are located, if only this one additional feature is required.

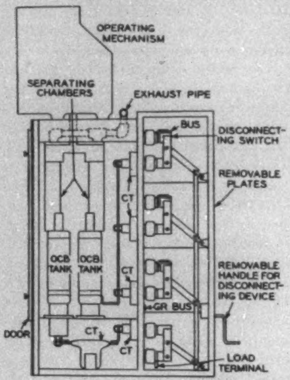

Figure 1. Cross section, metal-enclosed gear

CT—Current transformer

Speed of Operation

Circumstances under which a very short duration of the fault is most desirable will be discussed later. From the standpoint of circuit breaker operation, the element of time is broken down into two parts:

(*a*). Arcing time.

(*b*). Dead time.

With the addition of proper arc-control devices discussed above, minimum arcing time may be expected. Many old-style mechanisms are adequate to operate modernized breaker contacts, but have a dead time (defined as the interval from energizing the trip coil until contacts part) of several times the new arcing time. Marked reductions in dead time may usually be obtained by relatively simple modifications to the trip mechanisms, but these changes rarely permit reaching the minimum dead time provided by new mechanisms. Since most such old breakers were operated by non-trip-free mechanisms, modernization, particularly of higher-capacity circuit breakers, almost universally includes the addition of new high-speed trip-free mechanisms in order to secure maximum benefits. The performance which may be anticipated from a breaker modernized in this manner is practically the equivalent of that of a completely new breaker.

Reduction of Oil Hazard

The relation of oil quantity to fire hazard is a popular subject for discussion among those connected with the electrical industry and it is the general consensus of opinion that the search should continue for a noninflammable material for circuit-breaker use. A proper evaluation of the fire hazard in a station will by no means result in oil breakers rightly being singled out for criticism. The use and location of all combustible insulation material in the station or apparatus design and construction should receive equally careful attention. Under certain conditions the products of combustion of such materials may more seriously reduce the level of nearby insulation than those from oil itself.

Moderate-voltage low-oil-content breakers of high interrupting ability have been regularly used in large switching stations for many years, and have established a high level of performance and reliability. Since they are as economical of space as of oil, they find application in many cases of station modernization where it is necessary to scrap obsolete equipment, particularly where space is limited.

Development work is progressing rapidly on several types of high-capacity circuit breakers requiring no oil. Breakers of the same general configuration as the low-oil-content type in which water instead of oil acts as the interrupting medium, have been developed in ratings up to 1,500,000 kva at 15,000 volts. Tests have shown the same speed of operation and reliability of interruption as the low-oil-content breaker. Trial installations have been in service for several months, establishing a very satisfactory operating record. These breakers will fit into the same space as the low-oil-content type breakers referred to above and are favored by some users as a means of modernizing old breakers of that class.

Safety in Personnel

As long as those entrusted with the job of controlling the production and distribution of electrical energy are human beings, we may expect occasional cases of erratic and unexplainable performance. The examples of this limitation which come to attention most frequently involve the operation of the wrong disconnecting switches. At times these result in nothing more serious than tripping out one machine, or bus section, but too frequently in serious personal injury and considerable damage to nearby electrical equipment. A recent investigation of several cases disclosed the fact that in a majority of instances, the person involved was suffering from some kind of temporary emotional disturbance which apparently interferred with the mental processes accompanying even calm routine action to which he was accustomed. This is a condition which is definitely beyond the control of any employer, and from experience has been shown to affect even the higher-grade workers who are expected to think for themselves. It, therefore, appears obvious that a reduction in troubles of this kind can be expected only to the degree to which

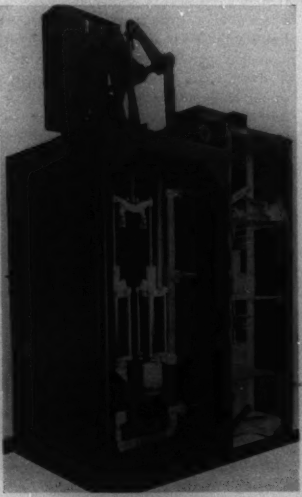

Figure 2. Metal-enclosed unit

foolproof mechanical safeguards are provided to assist the human mind when necessary, in making correct decisions.

The application of interlocks to ensure operation of correct disconnecting switches is by no means new. However, it has reached an all-time high for simplicity and effectiveness in modern metal-enclosed switchgear where six disconnecting switches are operated from one mechanism. This type of gear provides a simple, positive, and foolproof means of interlocking switches with the circuit breaker, to ensure proper sequence of operations. Gang operation safeguards against pulling two switches in one circuit and one in another. Cell-door interlocks prevent access to the circuit breaker until the switches are fully open and everything in the cell dead. And, finally, the operator is at all times separated from the switches which he is operating by a steel barrier.

Figure 1 is a cross section of such an equipment, showing the metal-enclosed busses, circuit breakers, disconnecting switches, and current transformers.

Insulation Level

Until recent years, the insulation test most commonly used for generator-voltage switching stations with an operating voltage in the 15 kv class was the 36 kv. More recently the trend has been toward a higher level, usually 54 kv, or the test value corresponding to the next higher voltage rating. Proper co-ordination of the insulation strength of various pieces of apparatus is most readily obtained in a complete metal-enclosed equipment. In many cases, the use of such steel construction has made it possible to secure the greater clearances necessary for the higher insulation level without requiring additional over-all space. Complete phase segregation by means of steel barriers throughout provides the maximum in safety, and permits application with maximum benefits of the various protective means to be discussed later.

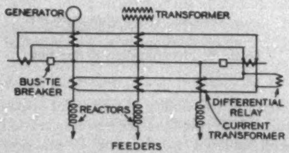

Figure 3. Differential protection applied to one bus section

Protection

Protection may be divided into two classifications, preventive and curative. The whole physical design as already discussed is bound up in preventive protection, but in addition other factors external to the gear must be considered.

The control of voltages due to lightning has received much study and as the literature has much regarding the treatment of this problem it will not be further discussed here.[1]

Prevention of serious overvoltages from other causes is a problem of the design of electrical connections and will be discussed later.

The application of curative protection is a function of the importance of the station. In an important station, such as is being considered, continuity of service is of utmost importance and therefore it is almost universal practice to use only such protection as can definitely distinguish between troubles in the protected area which must be cleared and those outside which must not be allowed to disturb anything in the area. Fast action is desirable in clearing a fault in that the damage to the gear and the probability of communication to other parts of the gear is reduced. If a study of the system shows that instability can occur if the fault duration is excessive, then fast clearing is imperative for loss of stability may mean an extremely serious disruption of service.

One of the simplest schemes in principle is the fault bus which, unfortunately, is one of the most difficult to install properly to obtain the desired results. Every element of the switching structure is insulated from ground and sections are insulated from each other. Each section is then provided with a ground through a current relay. If the structure is so designed that any fault must start as a line-to-ground fault, then the fault current must flow through the ground-current relay which causes the opening of the switches necessary to isolate the section in trouble. Very fast and reliable relays are available for this application so that faults can be cleared very rapidly with no danger of ever tripping at any but the right time. It can be shown that voltages of dangerous magnitude can be obtained on the ground bus and everything connected to it when a fault occurs. By the use of properly proportioned capacitors to ground at the right points the voltage can be held to a safe value. The practical difficulties of insulating an existing structure are so great as practically to eliminate it from consideration on a modernization program. Even if the structure is yet to be built, the difficulties are great and the apparatus is subject to accidental grounds on the structure which may by-pass the relay, making it inoperative. Therefore, the use of this apparently fine scheme has been rather limited.

The most common bus protection in use is the differential system, which may take any of several forms. Fundamentally the scheme consists of the addition of currents in all conductors connected to a bus section, as illustrated in figure 3. If a fault occurs outside of the section the incoming currents equal the outgoing, so the net sum is zero. A fault inside of the section causes a balance of current flow inward and the sum registered is equal to the fault current. The summation current is caused to flow through a relay which can trip all breakers feeding that section. All types of faults are covered by this type of protection, as each phase is treated independently. If the line-to-ground fault current is held to a low value a more sensitive relay can be used in a zero-sequence circuit for better ground protection. The major difficulty encountered in the application of this type of protection is that of obtaining accurate current transformers. At any given burden and primary current, duplicate transformers will all have about the same current ratio, but if different currents flow the ratios will vary, even with the same burden on each transformer. This variation in ratio will cause a net current to flow in the relay circuit during a fault outside of the protected area and if the variation is great enough the relay will operate. Therefore, if a simple overcurrent relay is used in the differential circuit care must be taken to use current transformers which maintain a nearly uniform ratio for the full range of possible currents.

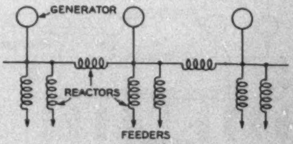

Figure 4. Straight bus

Inasmuch as the current transformers in a bus differential installation will not all be working at the same value of primary current in the event of a through fault, a certain amount of differential current will flow through the relay circuit in such a case. The magnitude of this current will, of course, vary with the current transformers used, the amount of primary current encountered, and will be further influenced by whether or not an offset wave having a d-c component is present. The effect of this undesirable differential current upon the operation of the protective equipment can be eliminated in several ways, depending upon the requirements of the problem. In many cases it has proved satisfactory to use a plain overcurrent relay with a relatively high setting. Other cases can use percentage differential relays similar to those in common use for transformer and generator protection obtaining restraint from proper grouping of the various current-transformer secondaries. Where high-speed protection is a requisite and neither of the two previously mentioned arrangements is deemed entirely adequate, there is available the harmonic-current-restrained relay which prevents relay operation in the case of current-transformer breakdown on a through fault, because of the distorted wave form of the current in the differential circuit. This current is made up of a difference in the exciting components required for the different current transformers and is rich in second and third harmonics which are used by means of a filter circuit to prevent relay operation.

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[1] For numbered reference, see end of paper.

Errors can be introduced in current transformers by the close proximity of other conductors carrying heavy currents which may cause false tripping when a simple overcurrent relay is used or may cause a long blocking interval on a harmonic-restraint relay to prevent its proper operation. This difficulty can be overcome by proper current-transformer design, by wider spacings, or by magnetic shielding.

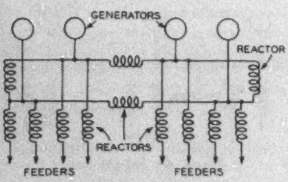

Figure 5. Ring bus

If every feeder circuit is equipped with a current-limiting reactor it is often possible to apply an impedance relay for bus protection. Current transformers are used only in the circuits which provide the major part of the short-circuit current and the secondary currents are added together and the sum passed through the current coil of an impedance relay. The relay is adjusted to operate if the equivalent impedance to the fault is less than the minimum possible impedance to a fault outside of the protected area. If the indicated fault impedance exceeds this value the fault is an external one and the relay does not close its contacts. High-speed operation can be obtained with this method of relaying. Current transformer errors cannot cause false operation on feeder faults but may on faults on a circuit from which current is taken for the relay. Careful consideration of each application is necessary on this point.

A system of protection which seems to have great possibilities consists of photoelectric relays so placed that any possible arc will throw light on a photoelectric tube. Usually there will be a large differential between the normal light level and the light produced by a short-circuiting arc and this difference can be used to differentiate a fault condition from normal conditions.

When the light of the arc falls on the tube all breakers on the affected bus section are tripped. This system can be made to operate fast and tests indicate it to be very effective in its selection of faults. Its principal disadvantage seems to be the lack of experience with its use on an actual system.

Electrical Connections

The design of electrical connections of a generating station can be such as further to limit the physical damage due to a short circuit, to simplify relay application, and what is more important, to reduce or eliminate service outages.

Short circuits in a switching equipment usually start line to ground. The magnitude of fault current for this type of short circuit can be reduced without disturbing the normal operation of the station by the use of a neutral impedance. This reduction is desirable in that it reduces the damage at the point of fault, reduces the probability of spreading the damage to other points, and reduces the strain on the switching equipment.

The most common neutral impedance in use is a pure resistance of a moderate value. The use of a high resistance approaches a condition of isolated-neutral operation which is known to produce dangerous over-voltages when a considerable transmission system is connected to the bus at generator voltage. This should be considered in the selection of a grounding resistor.

Reactors have been used and if of a low ohmic value are very successful and are more economical than an equivalent resistor. If the fault current is reduced to less than 25 per cent of the three-phase short-circuit current serious overvoltages can be expected even though no transmission circuits are connected directly to the bus.

If the zero-sequence network is limited to the station, that is, if all feeders are connected to the bus through transformers, it may be satisfactory to operate with an isolated neutral. Some stations have been operating in this manner for many years with great success. It is known that with low values of capacitance to ground and moderate values of neutral reactance voltage troubles can occur. It is also evident from limited experience that if the impedance approaches infinity that successful operation has been obtained. The limiting conditions are not very well known and, therefore, the initiation of such operation should be considered as experimental with a high degree of probability of successful operation. The results of successful operation with isolated neutral are a practical elimination of damage and spread of damage from a ground fault and a possibility of continued operation during the fault and until it is convenient to isolate the affected spot.

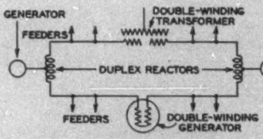

Figure 6. Modification of ring bus

It is usually desirable and sometimes necessary to reduce the short-circuit current in faults involving more than one phase. It is also desirable to so set up the bus that any fault can be isolated without materially disturbing service. These ends are both approached by use of a sectionalized bus. There are three general methods of arranging a sectionalized bus which are known as straight bus, ring bus, and star bus.

The straight bus is, as the name implies, a series of bus sections with reactors and breakers to connect them, as shown in figure 4. If the power supply is well distributed between bus sections and if all major loads are tapped off of at least two sections a bus fault properly relayed will not cause a serious loss of either power supply or load. That is, service would not be materially disturbed. If the affected section is any but an end section the isolation of the fault will split the station so that parts of it are connected only at the load. A careful study should be made to be sure that this does not cause instability between units of the same station.

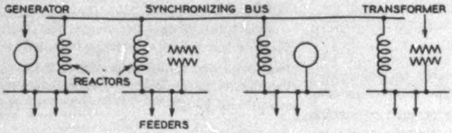

Figure 7. Star bus

Frequently a station operating with this type of bus is supplied with a duplicate bus to be connected in case of failure on the main bus. When good bus relaying is used it seems desirable to put the reserve bus in regular service to increase the number of bus sections and decrease the probability of an outage when a fault occurs. It is usually a simple matter to connect a main and reserve bus together with reactors to make a ring bus.

The ring bus is a series of bus sections connected together to form a continuous ring as shown in figure 5. With this arrangement the station is not split by the loss of one bus section. It is desirable to arrange the load so that as nearly as is possible each bus section has equal load and power supply. As this usually cannot be accomplished completely a transfer between bus sections is obtained and if reactor ties are used, there will be a variation in voltage on different bus sections. This regulation is less on a ring bus than on a straight bus, as there are two paths of power flow between any two points.

A modification of the ring bus is shown in figure 6 which prevents the total loss of any power supply when a bus section is lost. All large transformers are built with two low-voltage windings and connected to two bus sections. Each generator is built with a double winding or supplied with a duplex reactor. This is an economical arrangement for a steam plant, as generator reactors are usually used due to the low machine reactance and one reactor serves for both machine and bus tie.

The star or synchronizing-bus arrangement is illustrated in figure 7. The station is divided into independent sections which are each connected to a synchronizing bus through a reactor which is usually of a fairly high value. Loss of one section is equivalent to the loss of a section of a simple ring bus in that the generation and load on that section only are lost. If all load centers are connected to at least two sections no load is lost. The station is not split even if more than one section is lost. The loss of the synchronizing bus, however, splits the station into small units and the short-circuit current on this bus is apt to be very high. The regulation between sections of the star bus is often greater than it would be with the ring bus but under some conditions it may be less.

Most recent installations or modernizations have made use of either the ring or star bus arrangements and the decision of which to use has rested on local conditions and requirements. The trend in either case is to use a greater number of sections to minimize the effect on the system of the loss of one section.

It has been pointed out that reactors are often necessary to reduce the short-circuit current to a reasonable value. Bus-tie reactors are also desirable to increase the transient regulation between bus sections and thereby minimize the effect of that fault on one section on other sections and on the load voltage. It is desirable to ride through a fault without tripping undervoltage releases on any motors. Balanced against these desirable characteristics are the undesirable ones of increased normal regulation and decreased stability factors. The ability of two machines or group of machines to maintain a stable connection varies inversely with the impedance between them. A careful study should be made to co-ordinate bus connections, system connections, and relaying to ensure against loss of stability and resultant outages to power users.

Conclusion

The modernization or construction of any large switch house should take into consideration not only the physical structure with a view to minimize faults but also system connections and auxiliary equipment with a view to prevent serious outages to power users. Equipment and knowledge is available to design the apparatus and system to successfully meet any set of conditions which may be encountered.

Reference

1. PROTECTION OF STATIONS AGAINST LIGHTNING, L. V. Bewley and W. J. Rudge. *General Electric Review*, August and September 1937.

Discussion

For discussion, see page 778.

Modernization of Switch-House Design, Consolidated Edison Company of New York, Inc.

A. M. de BELLIS
MEMBER AIEE

IN THE past two or three years the question of modernization of generating stations and station equipment has been discussed liberally in the technical literature and in technical committees. It is the purpose of this paper to review the principal features of a modernization program undertaken by the Consolidated Edison Company of New York and its associated companies.

In introducing this subject a brief historical sketch of the development of such a program should prove of interest to those faced with the problem of system modernization.

Historical

The Consolidated Edison system furnishes electric service to all of Greater New York, with the exception of Staten Island, and to most of Westchester County.

It serves a population of 8,000,000 in an area of approximately 500 square miles.

Its nine generating stations have an installed capacity of 2,400,000 kw and produce annually approximately $6^1/_2$ billion kilowatt-hours, with a peak load estimated for the year 1939 at 1,715,000 kw.

Approximately 70 per cent of the total generating capacity supplies a 60-cycle load which consists largely of residential, commercial, small power, and traction.

The remaining generating capacity supplies, at 25 cycles, a large traction load which includes all of New York City trunk line railroads and, through rotary-converter substations, supplies a residential and commercial d-c load, mostly in Manhattan.

Obviously, in a system of such magnitude, there are to be found generating stations which vary considerably in age, size, type of design, and function.

Figure 1 shows the location, size, and the period in which the various stations of the New York system were originally built.

The first active planning for station modernization was undertaken in 1934 when it became necessary to make provision for the growing Manhattan 60-cycle load, and it was decided to install 60-cycle high-pressure topping units in Waterside No. 2, a 30-year-old station which had accumulated an excess of 25-cycle capacity due to the gradual replacement of 25-cycle load by 60-cycle load. Rebuilding of the Waterside No. 2 switch galleries was started in 1935 and will be completed in 1940.

Planning for the modernization of the Sherman Creek station was begun in 1935 and construction work for the rebuilding of the switch galleries was started in 1937, this being the first step in a program which includes the rebuilding of 40,000 kw of 25-cycle generators for operation at 60 cycles and the installation of 60-cycle topping units.

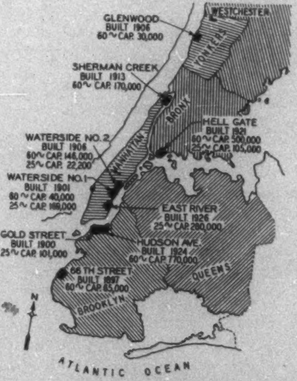

Figure 1. Generating stations owned by the Consolidated Edison system

Similar plans have been under consideration for the eventual revamping of the Gold Street, 66th Street, and Glenwood generating stations.

At the Hell Gate station, plans for the installation of bus differential protection and for the reinforcing of the station grounding system were started in 1934 and construction work on these improvements was in progress when the bus failure of January 1936 occurred.

As a result of this experience, the Hell Gate switch galleries are being completely revamped and minor improvements have been made to the Hudson Avenue station switch galleries.

General Design Features

In each station the type of design which has been adopted for the modernization of the switch galleries has been influenced not only by physical limitations of existing structures and existing types of design, but also by the necessity of maintaining the highest possible degree of station safety and service reliability while rebuilding operations were in progress.

In all cases, however, it may be said that as a result of past experience and the advancement in the art since the various stations of the Consolidated Edison system were built, the major objective has been that of securing a greater sectionalization of the switching equipment than previously existed.

The most important of the various steps which have been taken in order more effectively to confine to a relatively small section of the switch galleries the damages caused by equipment failures may be summarized as follows:

1. Improved physical sectionalization by means of fire walls and fire doors. The switch galleries have been divided in sections and, wherever possible, direct passage between sections has been eliminated. Switching equipment which is normally open has been provided on opposite sides of the fire walls between sections so that failure in one section is not likely to spread to the next.

2. Extensive electrical sectionalization of the main busses. This has resulted in a greater number of bus sections being available in a given station. Generator connections to the bus sections have been rearranged whenever necessary to secure a better balance between feeder and generator capacities. The loss of any one bus section will not seriously affect the station generating capacity and will result in a minimum feeder outage with no serious effects insofar as a given load area is concerned.

3. Use of the single-bus arrangement in preference to the double bus which had been more generally used in the past. This arrangement has made it possible to secure

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a greater sectionalization of the equipment within the various sections and has greatly reduced the number of oil circuit breakers required. Wherever possible, the high-duty circuit breakers which connect directly to the busses and which, in general, contain relatively large quantities of oil have been segregated into small groups, in separate rooms, thereby reducing and localizing the fire hazard.

Although oil-circuit-breaker performances have been generally satisfactory, some consideration is now being given to the possible use, in the future, of oilless breakers so as to reduce still further the fire hazard.

4. Metal-enclosed equipment of the group-phase type of construction, with each phase in a separate housing, has been used wherever possible.

5. Bus differential protection and high-speed relaying have been provided as additional means of localizing station faults and reducing to a minimum the destruction caused by such faults. In some cases the station grounding systems have been improved.

6. Ventilating systems have been improved so as to maintain proper isolation between sections and to facilitate the clearing of smoke and fumes in the event of fire. In some cases a water-spray system of fire protection has been provided for the better control of and to localize oil fires.

7. Power-supply systems for station auxiliaries and for generator excitation have been sectionalized in order to reduce to a minimum the hazard of a serious station shutdown resulting from failures in these systems.

What follows is a brief description of the modernization plans as developed for the individual stations.

Waterside No. 2 Station

This station was originally designed for ten turbogenerators and an ultimate station capacity of approximately 106,000 kw at 6,600 volts, 25 cycles.

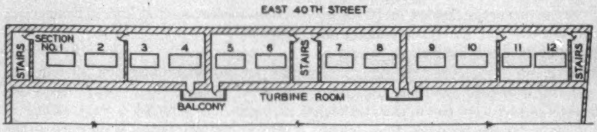

EAST 40TH STREET
SECTION NO. 1
2
3
4
5
6
7
8
9
10
11
12
STAIRS
STAIRS
STAIRS
STAIRS
TURBINE ROOM
BALCONY

Figure 3. Waterside No. 2—typical feeder floor

The switching equipment was of the double-bus group-phase arrangement and masonry compartments were used throughout. Connections to the main and auxiliary busses were of the familiar H-type design, each feeder group consisting of two selector oil circuit breakers, a short stub bus, and two feeder breakers, one for each of two feeders.

By 1934 the installed turbogenerator capacity had been increased to 152,000 kw and the 25-cycle voltage had been changed from 6,600 volts to 11,400 volts.

Although various improvements had been made to the switching equipment in order to meet the higher voltage requirements and the increased duty imposed upon the breakers, the main features of the original design had been maintained.

The original auxiliary power and excitation systems were still in existence and consisted of separate 250-volt d-c power and excitation busses supplied from motor generator sets and motor-driven exciters, respectively, with separate d-c station ties and standby batteries as back-up protection.

In accordance with present plans, the switch galleries are being completely rebuilt for operation at 13,200 volts, 60 cycles. The ultimate station capacity will be approximately 312,000 kw and will consist of seven or eight generators, four of which will be topping units of

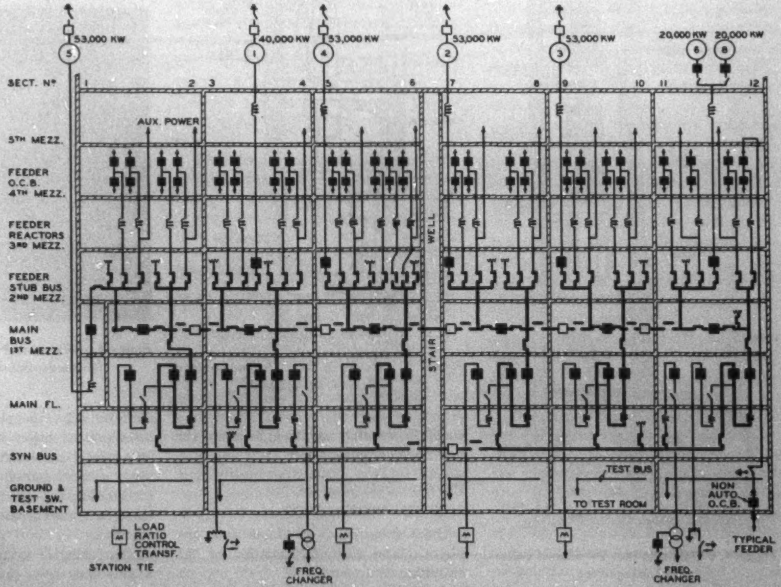

53,000 KW
5
40,000 KW
1
53,000 KW
4
53,000 KW
2
53,000 KW
3
20,000 KW
6
20,000 KW
8
SECT. Nº
1
2
3
4
5
6
7
8
9
10
11
12
AUX. POWER
5TH MEZZ.
FEEDER O.C.B. 4TH MEZZ.
FEEDER REACTORS 3RD MEZZ.
FEEDER STUB BUS 2ND MEZZ.
MAIN BUS 1ST MEZZ.
MAIN FL.
SYN BUS
GROUND & TEST SW. BASEMENT
WELL
STAIR
TEST BUS
TO TEST ROOM
NON AUTO O.C.B.
LOAD RATIO CONTROL TRANSF.
STATION TIE
FREQ. CHANGER
FREQ. CHANGER
TYPICAL FEEDER

Figure 2. Waterside No. 2—main connections

53,000 kw or larger, and the balance will be existing low-pressure 25-cycle units rebuilt for 60-cycle operation.

Bus Arrangement

The scheme of connections adopted for the 60-cycle equipment is a modified type of main and synchronizing bus arrangement in which the generators are connected directly to the main busses.

The main bus is divided in 12 feeder-bus sections and the synchronizing bus is divided in two sections as shown on figure 2.

During peak-load conditions the feeder-bus sections are to be tied in pairs through automatic bus-tie breakers, thus operating as a six-bus-section station and the synchronizing bus is to be operated in two sections. Under these conditions, each bus section will be supplied from three independent sources: a generator, an interstation tie, and the synchronizing bus. During off-peak load conditions the feeder busses may be tied in groups of four, thus operating as a three-bus-section station. Under the same conditions, the synchronizing bus will be operated in one section.

The station ties, being connected to the synchronizing ties between the main busses and the synchronizing bus, offer a means of transferring power between generating stations independently of the feeder busses and offer the additional advantage of rendering all station ties available to any feeder-bus section without impairing the sectionalization of the main busses.

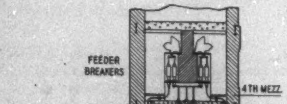

FEEDER BREAKERS
4TH MEZZ.
3RD. MEZZ.
SELECTOR BREAKERS
2ND MEZZ.
MAIN AND AUXILIARY BUSSES
1ST MEZZ.
EXCITERS
MAIN FLOOR
FEEDER REACTORS
SYN. BUS FLOOR
EXCITATION BATTERY
BASE'M'T FLOOR

Figure 4. Waterside No. 2—original switching arrangement

Each feeder-bus section supplies four outgoing distribution feeders arranged in two feeder groups and each group is connected to the main bus through a group-feeder reactor and disconnecting switch.

Locating reactors between the bus and the automatic breakers on all outgoing feeders, station ties, and frequency changers, has effected a large saving in breaker costs by reducing the duty on the breakers to a point where existing breakers could be readily modified to meet the new rating requirements.

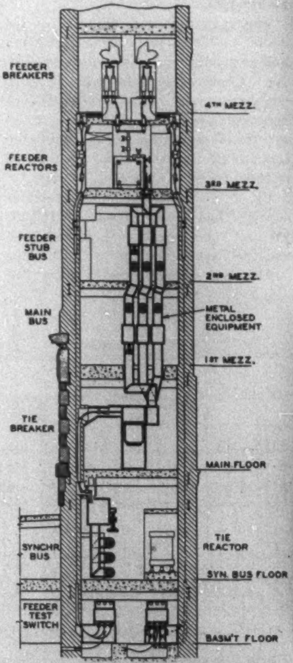

FEEDER BREAKERS
4TH MEZZ.
FEEDER REACTORS
3RD MEZZ.
FEEDER STUB BUS
2ND MEZZ.
MAIN BUS
METAL ENCLOSED EQUIPMENT
1ST MEZZ.
TIE BREAKER
MAIN FLOOR
SYNCHR BUS
TIE REACTOR
SYN. BUS FLOOR
FEEDER TEST SWITCH
BASM'T FLOOR

Figure 5. Waterside No. 2—modernized switching arrangement

Physical Sectionalization of Equipment

Great stress has been placed upon the physical and electrical isolation of the switching equipment.

Figure 3 shows how the switch galleries have been divided longitudinally in six major sections by means of fire walls and fire doors.

No direct access is provided between alternate major sections, the only access between these sections being by means of open balconies located outdoors or in the turbine room.

B
SYN. BUS
SEC. No 2
4

Figure 6. Waterside No. 2—metal-enclosed synchronizing-bus equipment

ASSEMBLY 33
MAIN FOR BUS SEC. 3W.
9653
9656

Figure 7. Waterside No. 2—metal-enclosed feeder-bus equipment

Essentially, the electrical equipment, with the exception of the synchronizing bus, has been isolated physically into three separate switch galleries.

Likewise, the synchronizing-bus equipment has been isolated in two separate sections.

The galleries occupy six floors and means have been provided to secure, if possible, a vertical isolation of the major equipment within each section.

For this purpose gas seals have been used between the various floors and it is expected that they will help to localize to any one floor the damage caused by equipment failures.

High-duty breakers are used only for bus-tie and generator connections. To reduce the fire hazard these breakers have been segregated into small groups located in separate rooms. With the exception of the breakers on the main floor, under peak-load conditions, there will be only one such breaker energized and carrying load in any one room. On the main floor there will be two such breakers in any one room. In the basement, where the nonautomatic metal-clad oil-filled ground and test switch units are located and where eight such units are housed in any one room, a water-spray system of fire protection is being installed.

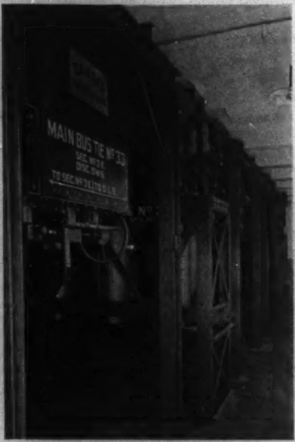


Figure 8. Waterside No. 2—metal-enclosed main-bus equipment

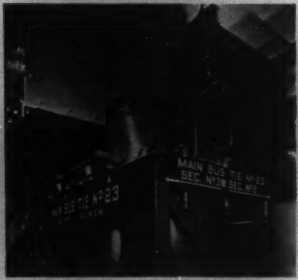


Figure 9. Waterside No. 2—metal housings for oil-circuit-breaker bushings

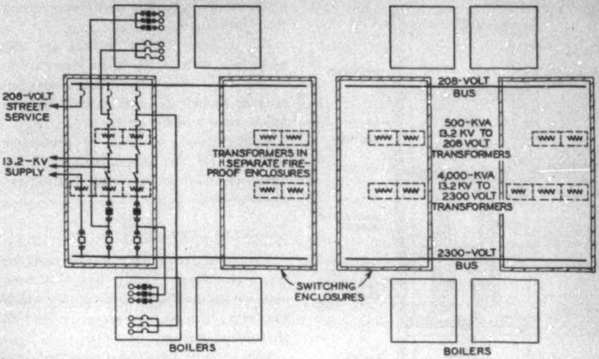


Figure 10. Waterside No. 2—auxiliary power supply

Figure 2 shows to what extent the electrical equipment has been physically isolated by means of walls and floors.

Electrically, the isolation between major bus sections is obtained at the fire walls by means of switching equipment which is normally kept open. For this purpose a bus-tie breaker and a disconnecting switch are provided on one side and a motor-operated disconnecting switch on the other side of the walls.

Where the bus goes through the fire walls, a gas-tight type of construction is used.

With this arrangement there are interposed between any two major bus sections, two distinct lengths of bus normally de-energized and physically separated from each other. It is felt that with this arrangement the effects of an equipment failure in any one major section are not likely to spread to other sections.

Metal-Enclosed Equipment

In the modernization of the Waterside switch galleries extensive use has been made of metal-enclosed equipment. Figures 4 and 5, which are cross sections of the original and the modernized switch galleries, show the simplification in station arrangement made possible by the use of metal-enclosed equipment.

Space limitations imposed by the existing building, and stringent requirements for service reliability and safety to personnel which had to be met, brought about the development of a new type of bus construction.

This new type of construction offers the advantages of a separated phase arrangement in a compact, simplified design which permits the use of factory-assembled equipment and has made it possible to lower installation and maintenance costs.

This new bus design consists, essentially, of a supporting structure on which are mounted a ground grid, the bus disconnecting switches, and the bus insulator supports which carry not only the bus conductors but also the bus enclosures.

To facilitate the use of factory-assembled equipment and to reduce installation costs, most of the supporting structures consist of unit-type fabricated-steel assemblies although, in some cases, use has been made of existing building steel and building walls.

The bus insulator supports which are the main members designed to withstand the short-circuit stresses consist of assemblies of four adjustable porcelain insulators mounted at 90 degrees to each other on a metal ring and brought to bear against the busses which are thus held in place.

In addition, the busses are taped for 23-kv insulation.

The metal bus enclosures, one for each phase, consist of cylindrical split covers which are bolted together and clamped around the insulator supporting rings, forming a dust-tight assembly.

This type of construction, in which the bus enclosures are not only entirely independent of the bus conductors and the bus supports, but are readily assembled after all bus connections are completed, offers a means of readily installing, inspecting, or repairing the bus equipment.

Phase isolation and metal-enclosed construction have also been used for the

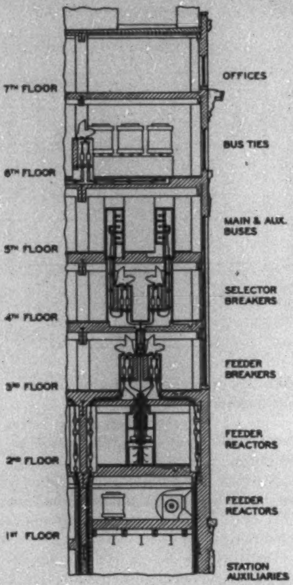

OFFICES
7TH FLOOR
BUS TIES
6TH FLOOR
MAIN & AUX. BUSES
5TH FLOOR
SELECTOR BREAKERS
4TH FLOOR
FEEDER BREAKERS
3RD FLOOR
FEEDER REACTORS
2ND FLOOR
FEEDER REACTORS
1ST FLOOR
STATION AUXILIARIES

Figure 11. Sherman Creek—original switching arrangement

bus disconnecting switches and the main oil circuit breakers which are connected directly to the busses.

Figures 6 and 7 are partial views of the metal-enclosed equipment used for the synchronizing bus and the feeder stub busses respectively.

A view of one of the main bus sections and a detail of the enclosures for the bus-tie oil-circuit-breaker bushings are shown in figures 8 and 9 respectively.

Relay Protection

Each of the 12 feeder-bus sections, that is, each group of four outgoing feeders, and each of the two synchronizing-bus sections are protected by a complete and overlapping scheme of high-speed current differential relays.

The bus differential relays act to trip all bus connections including the generators with a minimum time delay of approximately 0.05 second.

A local differential protection which overlaps and is selective with the main-bus and synchronizing-bus differential relays is used to protect the synchronizing ties which connect the main and the synchronizing busses.

As an additional protection against failure of the synchronizing-tie oil circuit breakers, the differential protection on these ties is backed up by overcurrent relay protection.

All outgoing feeder groups are also provided with a back-up overcurrent relay which clears the main feeder-bus section should a feeder circuit breaker fail to clear a feeder fault.

Conventional schemes of protection are used for the generators, frequency changers, station ties, and distribution feeders.

Auxiliary Power Supply

The basic plan of connections used for the high-voltage supply has also been used for the auxiliary power supply which has been changed from direct current to alternating current.

Two services have been provided, one at 2,300 volts and the other at 208 volts. For each service the ultimate bus arrangement will consist of eight load busses, one for each boiler, and a transfer bus for the reserve supply.

Each load bus will be supplied by its own power transformer and the transfer bus will be supplied by house generators for the 2,300-volt service and by ties to the street secondary network for the 208-volt service.

Station auxiliaries, with the exception of some emergency steam-driven boiler-feed pumps and condensate booster pumps, are all motor-driven.

Single-speed motors are used throughout and with the exception of two boiler-feed-pump motors, they are all started on full line voltage.

Most of the auxiliaries being boiler auxiliaries, the transformers and the switching equipment for the two services have been located at the load centers in the boiler house as shown on figure 10.

A minimum amount of automatic switching equipment has been used. For each boiler, for example, all 2,300-volt motors are supplied from one radial feeder. Nonautomatic starting switches are provided, of course, for the individual motors. All switching equipment for both service supplies is of the metal-enclosed type of construction.

Manual operation of the switching equipment on the supply circuits to the 2,300-volt and 208-volt busses is by means of supervisory control from the main control room in the switch galleries.

Physical sectionalization of the equipment has been obtained by installing the transformers and the switching equipment for each pair of boilers, in separate fireproof masonry housings.

Emergency lighting throughout the station is provided by groups of separate emergency outlets which are supplied by individual battery sets arranged for automatic operation and located at important operating points.

Other major changes which are part of the station modernization program include a new control supply which consists of duplicate control busses and switching equipment located in separate fireproof enclosures; the revamping of the control switchboards and the replacing of the present excitation-bus system by direct-connected main and pilot exciters on each generator.

Operating Experience

The first section of the rebuilt switch galleries went into service in May 1937

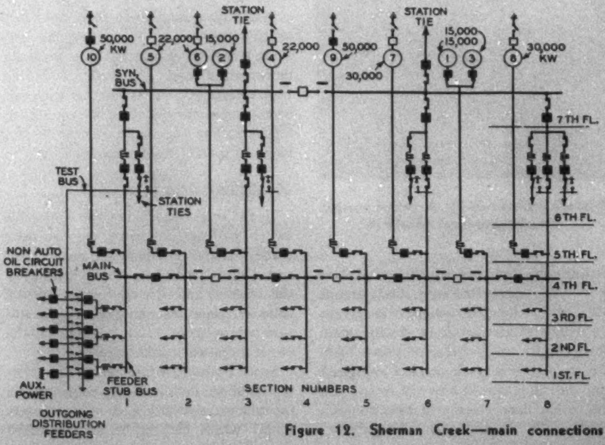

STATION TIE
STATION TIE
50,000 KW
22,000
15,000
22,000
50,000
30,000
15,000
15,000
30,000 KW
10
5
6
2
4
9
7
1
3
8
SYN. BUS
7TH FL.
TEST BUS
STATION TIES
6TH FL.
NON AUTO OIL CIRCUIT BREAKERS
MAIN BUS
5TH. FL.
4TH FL.
3RD FL.
2ND FL.
1ST. FL.
AUX. POWER
FEEDER STUB BUS
SECTION NUMBERS
1
2
3
4
5
6
7
8
OUTGOING DISTRIBUTION FEEDERS

Figure 12. Sherman Creek—main connections

and operating experience, so far, has been entirely satisfactory.

To what extent metal-enclosed equipment and fast relaying will contribute toward localizing the effects of equipment failures and safeguarding personnel as well as reducing to a minimum the damages caused by such failures was illustrated in November 1937 when a short circuit occurred on one of the frequency-changer circuits.

Each of the two frequency changers is connected directly to the synchronizing bus through a bus disconnecting switch, a reactor, and an oil circuit breaker.

At that time the necessary interlocks between the manually operated bus disconnecting switch and the oil circuit breaker were not completely installed.

With the frequency changer at a standstill, an attempt was made to close the bus disconnecting switch while the circuit breaker was not in the completely open position, the contacts on two phases being partially closed.

The disconnecting switches on the two phases arced over to ground causing a double-line-to-ground short circuit on the synchronizing bus. The fault was cleared by the synchronizing-bus differential relay in approximately 0.3 second of total clearing time, including breaker time. Feeder busses were not affected. The total fault current at the disconnecting switch was calculated to have been 56,000 amperes root-mean-square symmetrical current and the estimated instantaneous asymmetrical current 140,000 amperes.

The damage to the switches was limited to local burning of the stationary contacts and blades, and also burning and chipping of some of the insulators.

The outside of the switch housing showed no indication of damage.

On the inside of the housing, a slight burning showed where the switch arced to ground.

The insulated bus connections between the disconnecting switch and the bus as well as the bus and bus supports and the bus housings were undamaged.

However, beyond the metal-enclosed equipment the connections from the disconnecting switch to the oil circuit breaker are carried on the ceiling in three-phase compartments of the conventional type of construction with concrete barriers between phases and with bolted gasketed metal covers.

These covers were blown open by the gas pressure.

Operating personnel was not injured.

The damaged equipment was replaced in a few hours and the total cost of repairs did not exceed $2,000.

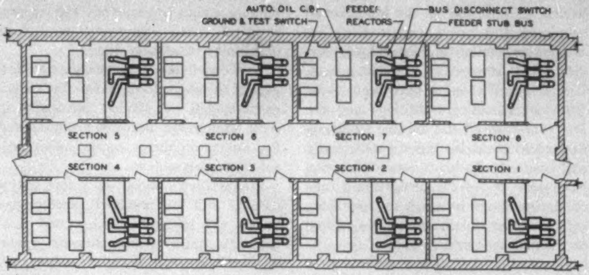


Figure 14. Sherman Creek—typical feeder floor

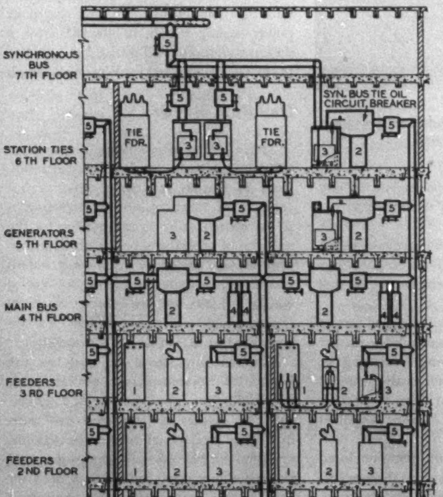


Figure 13. Sherman Creek—longitudinal section of switch galleries

1—Ground and test switch

2—Oil circuit breaker

3—Reactor

4—Potential transformer

5—Disconnecting switch

Sherman Creek Station

This station was originally designed for eight turbogenerators and an ultimate station capacity of approximately 145,000 kw, of which 40,000 kw were generated at 6,600 volts, 25 cycles, and the balance at 7,800 volts, 60 cycles.

Although the generation voltage for part of the 60-cycle supply was later raised to 13,200 volts, no major changes were made in the general station layout nor in the original arrangement of the switching equipment which, as shown in figure 11, is substantially a duplicate of the original Waterside design.

As part of the modernization program for this station which includes the installation of topping units, it is planned to rebuild the switch galleries for an ultimate station capacity of approximately 280,000 kw at 13,200 volts, 60 cycles, as shown in figure 12.

To date, the modernization work already completed consists of the rewinding of two 25-cycle generators for operation at 60 cycles and the rebuilding of the old 25-cycle section of the switch galleries.

Basically, the station layout for the

rebuilt galleries follows the fundamental requirements for equipment sectionalization and protection established for Waterside No. 2. Physically, however, a number of radical changes have been made. Structural building conditions and the fact that none of the existing switching equipment could be reused satisfactorily and economically in its present location have made it possible to develop a type of station design in which the switching equipment for any one circuit is arranged on the unit-type principle.

Essentially, this design isolates in a separate room all the main switching equipment related to a given circuit, such as bus disconnecting switches, oil circuit breakers, reactors, and ground and test switches.

From figure 13 which shows a longitudinal view of a typical major bus section, it can be seen how the switching equipment has been sectionalized and grouped in separate rooms.

Each room of the first, second, and third floors houses all of the equipment for one feeder group and all rooms are alike in design.

Likewise, the equipment for the generators and the station ties is located in separate rooms on the fifth and sixth floors respectively.

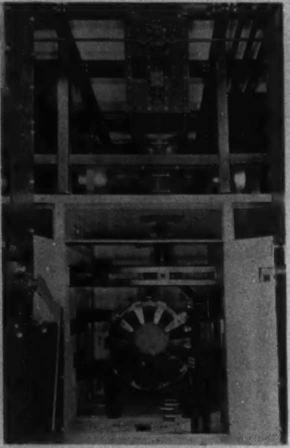


Figure 15. Sherman Creek—typical feeder-reactor installation

It is expected that this type of construction will offer some advantages from the standpoint of equipment sectionalization, station operation and maintenance, safety to personnel, and replacement of major equipment, as well as uniformity of station design.

As shown in figure 14 which is a typical plan of one of the feeder floors, the switch galleries will be divided physically in eight sections by means of fire walls and fire doors, no direct access being provided between sections.

Electrically, however, only four major sections will be provided because the busses will normally be operated connected in pairs through automatic bus-tie circuit breakers as shown in figure 12.

Metal-enclosed equipment is to be used almost entirely in the switch galleries, the only masonry compartments of any importance being those which house the reactors.

Figure 16. Sherman Creek—metal-enclosed bus equipment

A typical reactor compartment and a station-tie reactor with its connections to a metal-enclosed disconnecting switch are shown in figure 15.

The design of the metal-enclosed busses and the methods used to secure the proper electrical sectionalization between the major bus sections as well as the schemes used for bus differential relay protection are a duplicate of those already described for Waterside No. 2.

Figure 16 shows the metal-enclosed vertical bus runs and the bus disconnecting switches for a typical feeder-group installation.

Metal-enclosed feeder oil circuit breakers and ground and test switches are shown in figure 17.

In addition to the rebuilding of the switch galleries, other major changes which are part of the modernization program for this station include a revamping of the control switchboards, the installation of direct-connected main and pilot exciters on the generators to replace the present excitation-bus system, and the installation of a new auxiliary power supply which, in general, from a design standpoint will probably be similar to the one established for Waterside No. 2.

Figure 17. Sherman Creek—metal-enclosed switching equipment

Hell Gate Station

The modernization work planned for this station does not involve any additions to station generator capacity but consists of changes and improvements to the switch galleries undertaken for the purpose of securing a better sectionalization of the electrical equipment. This station has a capacity of 605,000 kw of which 105,000 kw are generated at 25 cycles, 11,400 volts, and 500,000 kw are generated at 60 cycles, 13,200 volts.

The switch galleries are built on the horizontal isolated-phase principle and, longitudinally, they are divided physically by means of transverse fire walls into nine sections of which six sections are used for the 60-cycle equipment and the remaining three sections are used for the 25-cycle equipment. The switching equipment is of the double-bus arrangement and the connections to the main and auxiliary busses are of the H-type design.

Masonry compartments are used throughout. In the original design the

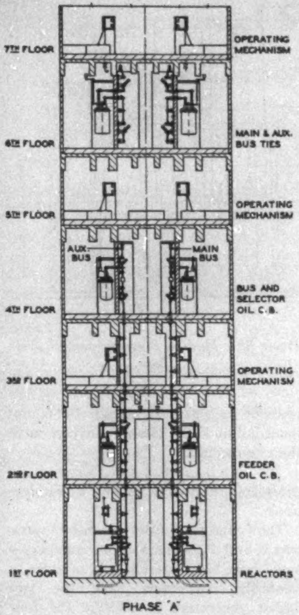

7TH FLOOR
6TH FLOOR
5TH FLOOR
4TH FLOOR
3RD FLOOR
2ND FLOOR
1ST FLOOR
OPERATING MECHANISM
MAIN & AUX. BUS TIES
OPERATING MECHANISM
AUX. BUS
MAIN BUS
BUS AND SELECTOR OIL C.B.
OPERATING MECHANISM
FEEDER OIL C.B.
REACTORS
PHASE 'A'

Figure 18. Hell Gate—original switching equipment

60-cycle busses were sectionalized electrically by bus-tie breakers and bus-tie reactors into four sections. The 25-cycle galleries are sectionalized in three sections. As shown in figure 18 the main and the auxiliary busses and related oil circuit breakers are located on the fourth floor with longitudinal walls separating the busses from the breakers.

Likewise, the bus-tie equipment for both busses is located on the sixth floor.

BUS REARRANGEMENT

In order properly to balance feeder, generator, and station-tie capacities and to provide the required feeder diversity to the various network areas it becomes necessary, under certain conditions, to operate both the main and the auxiliary 60-cycle busses.

As a result of the disturbance of January 1936 in which the trouble communicated between the main and the auxiliary busses, these busses are being rearranged and relocated.

From an operating standpoint the 60-cycle switching equipment will consist of a single bus which will be divided in 12 feeder-bus sections as shown in figure 19.

During peak load conditions the feeder-bus sections are to be tied in groups of three through automatic bus-tie breakers, thus operating as a four-bus-section station.

During off-peak load conditions the feeder busses may be tied in groups of six, thus operating as a two-bus-section station.

Generator connections to the bus sections will be rearranged in some cases to secure a better balance of feeder and generator capacities and the two 160,000-kw units will be reconnected so that each will feed two bus sections.

PHYSICAL SECTIONALIZATION OF EQUIPMENT

In order to reduce to a minimum the possibility of trouble on one bus section communicating to other sections, the switching equipment is being relocated as shown in figures 20 and 21.

With this arrangement the busses for each half of the station are completely isolated, being located on separate floors.

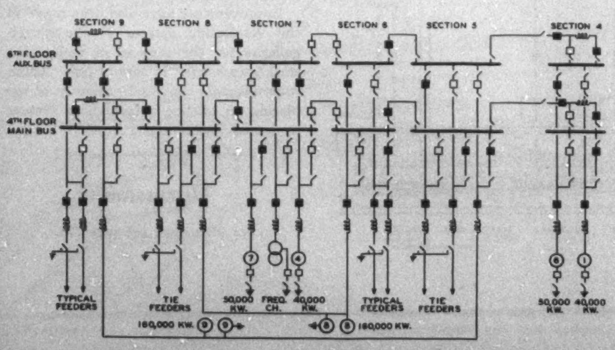
All bus-tie reactors, breakers, and selector breakers for six bus sections will be located on the sixth floor and the corresponding equipment for the other six sections will be located on the fourth floor.

Between major bus sections on the same floor, provision will be made for two separate transverse walls with fire doors and a passageway between walls. This will eliminate direct access between sections and it is expected it will reduce the possibility of communication of trouble from one section to the other.

To avoid outages during periods of maintenance and inspection of the bus equipment and to facilitate the reconstruction program, the H-type design of bus connections has been maintained and all circuits are provided with bus selectivity, being connected to the busses on the two floors.

However, risers to the sixth floor busses will be completely walled off from the busses on the fourth floor and on all circuits additional disconnecting switches in gas-tight enclosures will be installed on separate floors from the bus equipment so that between the fourth- and the sixth-floor busses there will be double disconnecting switches which will be operated open.

Figure 19. Hell Gate—main connections


SECTION 9
SECTION 8
SECTION 7
SECTION 6
SECTION 5
SECTION 4
6TH FLOOR AUX. BUS
4TH FLOOR MAIN BUS
TYPICAL FEEDERS
TIE FEEDERS
50,000 KW.
FREQ. CH.
40,000 KW.
TYPICAL FEEDERS
TIE FEEDERS
50,000 KW.
40,000 KW.
160,000 KW.
160,000 KW.

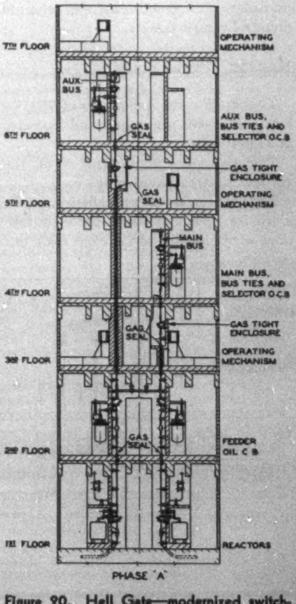

7TH FLOOR
6TH FLOOR
5TH FLOOR
4TH FLOOR
3RD FLOOR
2ND FLOOR
1ST FLOOR
OPERATING MECHANISM
AUX. BUS
GAS SEAL
AUX BUS, BUS TIES AND SELECTOR O.C.B.
GAS TIGHT ENCLOSURE
GAS SEAL
OPERATING MECHANISM
MAIN BUS
MAIN BUS, BUS TIES AND SELECTOR O.C.B.
GAS SEAL
GAS TIGHT ENCLOSURE
OPERATING MECHANISM
GAS SEAL
FEEDER OIL C.B.
REACTORS
PHASE 'A'

Figure 20. Hell Gate—modernized switching arrangement

In addition, the connections between disconnecting switches are to be made gas-tight where they go through the floors. With this arrangement, trouble in any one bus is not likely to communicate to the other bus.

In order to maintain the necessary segregation between floors and between sections, extensive changes are also being made to the ventilating system.

Bus Relay Protection

Each of the 12 feeder-bus sections is protected against phase-to-ground faults by a combination of partial-current differential relays with impedance and zero-sequence-voltage fault detectors.

The bus differential relays act to trip all bus connections including the generators.

All generators, bus ties, and tie feeders are included in the current differential circuits, while faults on outgoing feeders are detected by the impedance elements and the zero-sequence-voltage fault detectors differentiate between the busses on the sixth and the fourth floors.

Other changes included in this modernization program, most of which have already been completed, consist of the reinforcing of the station grounding system and the installation of larger generator-neutral grounding breakers with a physical isolation of these breakers in separate fireproof compartments.

Hudson Avenue Station

This station has a capacity of 770,000 kw in 60-cycle generators and operates at 27,600 volts.

The switching equipment is of the vertical isolated-phase type.

Physically, the switch galleries are divided by walls and doors into eight sections corresponding to the eight main bus and feeder sections as shown on figure 22.

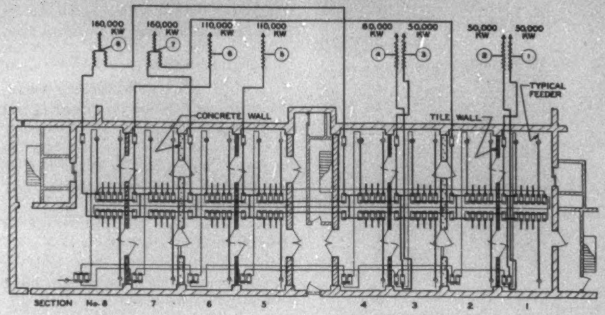


Figure 22. Hudson Avenue—typical phase floor

In the center, a fire tower with heavy brick walls and fire doors divides the switch galleries in two separate parts and prevents direct access from one part to the other.

Modernization work in this station has consisted primarily of the following:

1. Changes to fire walls.
2. Interchanging of generator connections.
3. Installation of bus differential protection.
4. Improvements to the ventilating system.

In order to secure a more effective sectionalization of the switching equipment and to prevent, if possible, the spread of damage caused by equipment failure, alternate fire walls have been changed from hollow tile to concrete. In addition, these walls have been equipped with sets of double fire doors.

It is expected that with these structural changes any damage caused by equipment failure is not likely to involve more than two sections.

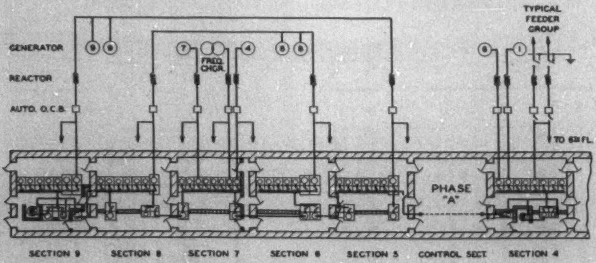


Figure 21. Hell Gate—typical selector-breaker floor

The switch galleries may, therefore, be considered as divided in four major sections.

The connections from generators numbers 6 and 7 to bus sections numbers 6 and 7 have been interchanged in order to establish connections from the two largest generators to each of the four major bus sections and also to provide a better physical sectionalization between the connections of these two large generators.

The bus arrangement in this station consists of sectionalized main and synchronizing busses.

Each main bus section is essentially an H-bus arrangement which, through automatic circuit breakers, is connected to four feeder busses and to its own generator and to the synchronizing bus.

Each of the H-bus sections have been equipped with current differential relays which act to trip all bus connections including the generator.

Improvements have also been made to the ventilating system of the switch galleries for the purpose of facilitating smoke scavenging in case of fire. These improvements consisted primarily of replacing an existing natural-draft system by forced ventilation.

Discussion

For discussion, see page 778.

Reconstruction of Switching Facilities at Essex Generating Station

D. W. TAYLOR
MEMBER AIEE

LOCATED on the Passaic River, three miles from the business district of Newark, N. J., the Essex generating station of the Public Service Electric and Gas Company was designed and constructed in 1915–16, to supply the load of the Newark and surrounding area at 13 kv with ties of approximately 20,000 kva to the neighboring Marion generating station. By 1924, six generators had been installed, totaling 214,444 kva, and the switch house had been extended to the ultimate of the 1915 plans.

During the growth of the system, a 26-kv outdoor substation and a 132-kv outdoor switchyard were added, the latter to tie in with the state-wide 132-kv transmission system which was interconnected through 220-kv with the Philadelphia Electric Company and the Pennsylvania Power and Light Company.

Progress in protective devices by 1935 had outmoded much of the station's equipment, and studies were started to determine the feasibility of applying modern protective schemes to the existing plant. As system conditions in 1936 required the installation of a superposed turbine generator and a third 132-kv line, the modernization studies were broadened to include a complete survey of the station's adaptability not only for these two immediate additions, but for future requirements.

At that time, the load of the 13-kv switch house was mainly that of the business and industrial area of Newark and vicinity, and was carried over 44 outgoing feeders and had a peak of 133,000 kva. The 26-kv switchyard carried a maximum load of 53,000 kva over seven feeders and was supplied from the 13-kv bus through transformers of 84,500-kva capacity.

Load estimates predicted a maximum 13-kv peak of 168,000 kva for future economical transmission at this voltage, the additional growth to be carried at 26 kv.

The 132-kv switchyard consisted of two 100,000-kva lines and two 45,000-kva transformer banks for interchange of bulk power.

Figure 1 shows the relation of the Essex generating station to its 13-kv load area and to the rest of the system.

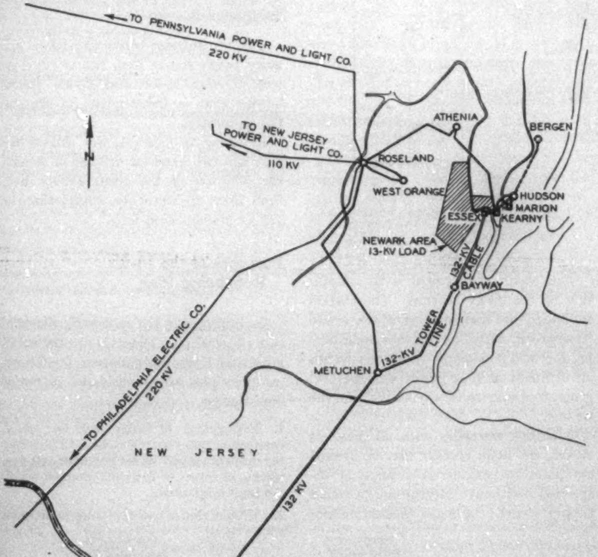

TO PENNSYLVANIA POWER AND LIGHT CO.
220 KV
N
TO NEW JERSEY POWER AND LIGHT CO.
110 KV
ATHENIA
BERGEN
ROSELAND
WEST ORANGE
HUDSON
MARION
KEARNY
ESSEX
NEWARK AREA 13-KV LOAD
132-KV CABLE
BAYWAY
132-KV TOWER LINE
METUCHEN
TO PHILADELPHIA ELECTRIC CO.
220 KV
NEW JERSEY
132 KV
TRENTON
PENNSYLVANIA
TO PHILADELPHIA ELECTRIC CO.
66 KV
BURLINGTON
132 KV
CAMDEN
LEGEND
GENERATING STATIONS
SWITCHING STATIONS
FUTURE SWITCHING STATIONS
PRESENT 132-KV TOWER LINES
FUTURE 132-KV TOWER LINES
PRESENT 132-KV CABLE
4 3 2 1 0 4 MILES

Figure 1. System map of Public Service Electric and Gas Company

Reasons for Rebuilding

That extensive rebuilding of the 13-kv, 26-kv, and 132-kv switching facilities was necessary is evident from the following summary of the then existing conditions.

1. Space was not available in the 13-kv busses for the proper location of current transformers for differential relays, which combined with the presence of many nonautomatic main breakers of inadequate interrupting capacity for automatic operation, made it impractical to provide bus protection. The layout was also unsuited for the most advantageous use of the 132-kv bulk power ties, and for future extensions.

2. Adequate segregation and isolation of equipment in the switch house to reduce the extent of oil-fire damage was lacking. One hundred seventy-six oil circuit breakers were housed on five floors of the 146-foot by 58-foot switch house without separating walls or barriers except that provided by the masonry cell work.

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D. W. Taylor is assistant electrical engineer in the electric engineering department of the Public Service Electric and Gas Company, Newark, N. J.

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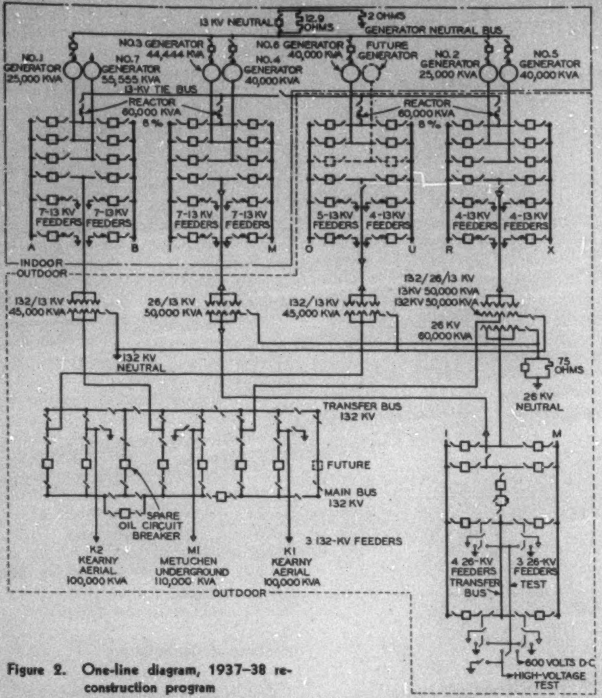

13 KV NEUTRAL
12.9 OHMS
2 OHMS
GENERATOR NEUTRAL BUS
NO.1 GENERATOR 25,000 KVA
NO.7 GENERATOR 55,555 KVA
NO.3 GENERATOR 44,444 KVA
NO.4 GENERATOR 40,000 KVA
NO.6 GENERATOR 40,000 KVA
FUTURE GENERATOR
NO.2 GENERATOR 25,000 KVA
NO.5 GENERATOR 40,000 KVA
13-KV TIE BUS
REACTOR 60,000 KVA 8%
REACTOR 60,000 KVA 8%
7-13 KV FEEDERS
7-13 KV FEEDERS
7-13 KV FEEDERS
7-13 KV FEEDERS
5-13 KV FEEDERS
4-13 KV FEEDERS
4-13 KV FEEDERS
4-13 KV FEEDERS
A
B
I
M
O
U
R
X
INDOOR
OUTDOOR
132/13 KV 45,000 KVA
26/13 KV 50,000 KVA
132/13 KV 45,000 KVA
132/26/13 KV
13KV 50,000 KVA
132KV 50,000 KVA
26 KV 60,000 KVA
132 KV NEUTRAL
75 OHMS
26 KV NEUTRAL
TRANSFER BUS 132 KV
FUTURE
MAIN BUS 132 KV
SPARE OIL CIRCUIT BREAKER
3 132-KV FEEDERS
K2 KEARNY AERIAL 100,000 KVA
M1 METUCHEN UNDERGROUND 110,000 KVA
K1 KEARNY AERIAL 100,000 KVA
OUTDOOR
I
M
4 26-KV FEEDERS
TRANSFER BUS
3 26-KV FEEDERS
TEST
600 VOLTS D-C
HIGH-VOLTAGE TEST

Figure 2. One-line diagram, 1937–38 reconstruction program

3. The control room was lacking in facilities for future additions and in need of modernization.

4. Oil circuit breakers were provided for four feeders and two transformer banks only in the 26-kv switchyard, the remaining three feeders making use of individual transformers and 13-kv switching. With increase of load, additional transformer capacity and bussing of all feeders would be necessary. Bus protection was also lacking.

5. The 132-kv switchyard was of the high, strain-bus construction with numerous crossovers, difficult to maintain, and with the possibility of a falling high-level connection, causing a total shutdown. The arrangement was unsuited for the future extensions.

The reconstruction program was started early in 1937 to be completed in two years.

Schematic Plan

The schematic plan developed is shown in figure 2. The 26-kv and 132-kv layouts are those developed over a period of 12 years in the 132- to 26-kv switching stations of the Public Service Electric and Gas Company.

The 13-kv arrangement is an adaptation of the 26-kv scheme. The station is divided into four sections, of two group busses each, with a tie bus for synchronizing and load balancing. Each section has an ultimate of four power sources, two generators, one transformer bank, and the tie bus.

Operating normally with all breakers closed, any main breaker may be opened manually for maintenance work or inspection, without interrupting a main supply source; a main breaker failure will clear only one bus or one-eighth of the feeders, in addition to its own generator or transformer, but that generator or transformer may be cut in again on the other group of the pair to carry load; and a fault on a feeder group bus will not clear any supply source from the system. In case the tie bus is cleared due to a fault, the four sections will be held in synchronism through the transformer banks and the 132-kv bus. The only main switching operations necessary are cutting generators in and out of service, as the transformers and tie bus are to be in service at all times except for inspection or maintenance.

The feeders to each substation are divided between the two group busses forming a section. This prevents:

1. Reducing effectiveness of tie-bus reactors.
2. Unbalanced loading of feeder cables.
3. Fault current in the station affecting the transmission system.

The transformer banks provide a primary power source from the 132-kv system to the 13-kv and 26-kv feeder busses, that is independent of the station generators.

Referring to figure 1, the 132-kv bus also has two external sources of power, the addition of the third 132-kv line, from Essex to Metuchen, completing the 132-kv transmission loop.

Purposes of the 13-Kv Rebuilding Plan

In transposing the schematic diagram to a physical plan adaptable to the existing switch house and property, the following principles were considered of major importance:

1. Segregation of equipment by space, barriers, or other means, to limit, if possible, the damage caused by an explosion, oil fire, smoke, or fumes to the equipment in which the fault originated.
2. Elimination of points of congestion, such

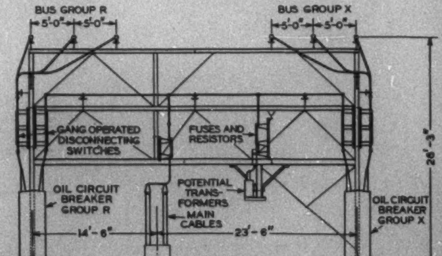

BUS GROUP R
5'-0"
5'-0"
BUS GROUP X
5'-0"
5'-0"
GANG OPERATED DISCONNECTING SWITCHES
FUSES AND RESISTORS
POTENTIAL TRANS-FORMERS
OIL CIRCUIT BREAKER GROUP R
MAIN CABLES
OIL CIRCUIT BREAKER GROUP X
14'-6"
23'-6"
26'-3"
GRADE

Figure 3. Thirteen-kilovolt switchyard—cross section of generator and transformer bays

as control or main-lead "bottle necks," where a fire, explosion, or external force in a small area might cause a total shutdown.

3. Reduction of the amount of oil in the switch house to the lowest possible quantity.

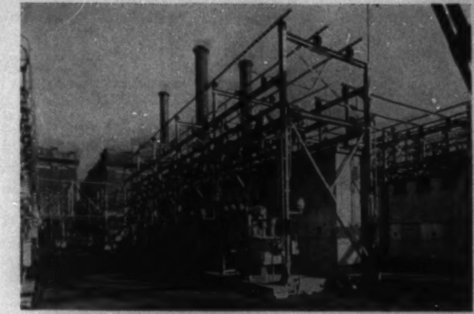


Figure 5. View of 13-kv switchyard

Development of the 13-Kv Plan

After making preliminary layouts, it became evident that only about half of the necessary equipment could be housed in the present building with ample spacing, segregation, and smoke and fire barriers. Rather than extend the building to almost double its size, it was decided to locate one half of the switching equipment entirely separate from the other half in an outdoor switchyard. This would eliminate, so far as possible, a major conflagration involving all of the station's switching facilities and, in addition, had the advantage of allowing the outdoor portion to be erected and cut in service with only minor disturbance to the existing indoor busses.

Insulation and Short-Circuit Duty

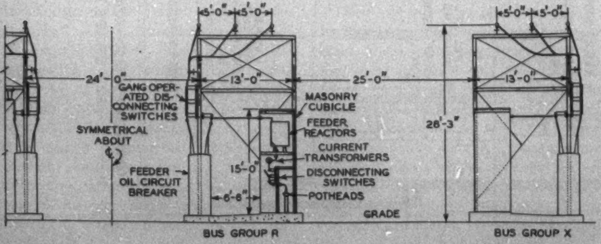
All new apparatus and equipment for 13-kv service was purchased with 23-kv-class insulation. Some of the existing indoor apparatus and equipment reused is of the 15-kv class. All main generator, transformer, and tie-bus breakers have an interrupting rating of 1,500,000 kva at 13 kv.

Outdoor 13-Kv Switchyard

The cross section of a typical generator and transformer bay, and the cross section through the feeder bays are shown in figures 3 and 4, respectively.

As an outdoor arrangement depends to a large extent on air-line distances for segregation, the spacing was made as ample as the available plot would permit, resulting in bus and lead spacing sufficient in general for 26-kv service.

Figure 4. Thirteen-kilovolt switchyard—cross section of feeder bays



The feeder-cable potheads, line disconnecting switches, current transformers, and feeder reactors were placed in masonry cubicles, which allowed the former indoor-type reactors and disconnecting switches to be used, and saved considerable space over an arrangement using outdoor oil-filled reactors. The cubicles are of masonry to eliminate any heating or magnetic difficulties that might be encountered by the use of a metallic housing.

The connections from three of the generators were routed direct from the turbine room to the outdoor switchyard, so that they are well separated from the generator leads to the indoor sections.

The main oil circuit breakers are 2,000- and 3,000-ampere type *GO-5A*. The feeder oil circuit breakers are 600-ampere type *GO-3*, of 500,000-kva interrupting capacity. All disconnecting switches are of the high-pressure type, those of 2,000 and 3,000 amperes capacity being of extra-heavy construction.

Flexible connections were used on both sides of the 2,000- and 3,000-ampere disconnecting switches to eliminate vibration or expansion stressing the oil-circuit-breaker bushings or disconnecting switches. Figure 5 shows a general view of the outdoor feeder section and figure 6 a view of the 2,000- and 3,000-ampere disconnecting switches, flexible leads, and the oil circuit breakers.

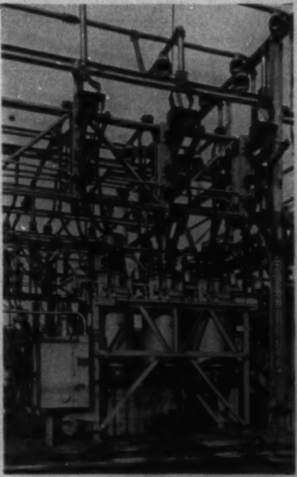


Figure 6. Two thousand- and 3,000-ampere 13-kv outdoor oil circuit breakers, disconnecting switches, and connections

Indoor 13-Kv Arrangement

By moving 15 of the 44 feeders and half of the generator and transformer connections to the outdoor yard, the space available for the large-capacity main breakers was more than three times that provided previously. The longitudinal sections, figure 7, compare the relative space occupied by the main equipment and feeder equipment before and after the rebuilding.

Referring to figure 7, the switch house is divided into two halves by walls from the first to the sixth floors, forming a corridor through the center of the building.

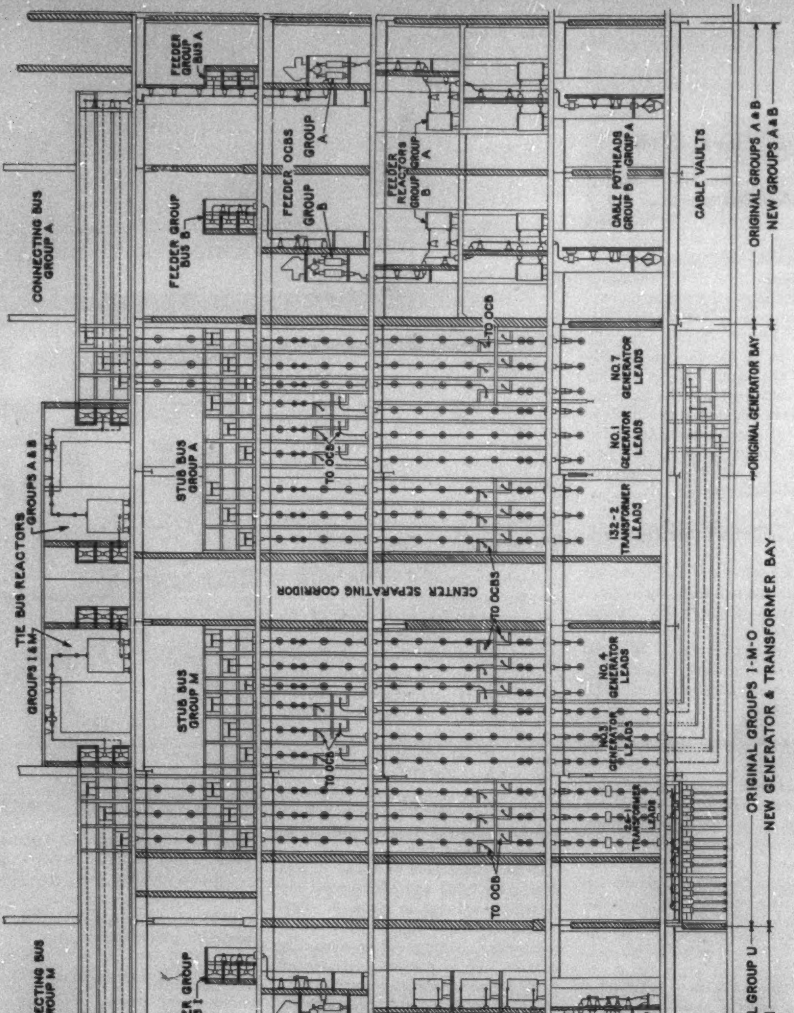

CONNECTING BUS GROUP A
FEEDER GROUP BUS A
FEEDER GROUP BUS B
FEEDER OCBS GROUP A
GROUP B
FEEDER REACTORS GROUP A
GROUP B
CABLE POTHEADS GROUP B GROUP A
CABLE VAULTS
TO OCBS
NO. 7 GENERATOR LEADS
NO. 1 GENERATOR LEADS
132-2 TRANSFORMER LEADS
STUB BUS GROUP A
TIE BUS REACTORS GROUPS A & B
GROUPS I & M
TO OCB
CENTER SEPARATING CORRIDOR
TO OCBS
STUB BUS GROUP M
NO. 4 GENERATOR LEADS
NO. 3 GENERATOR LEADS
24-1 TRANSFORMER LEADS
TO OCB
CONNECTING BUS GROUP M
FEEDER GROUP BUS I
FEEDER OCBS GROUP I
GROUP M
FEEDER REACTORS GROUP I
GROUP M
CABLE POTHEADS GROUP I
GROUP M
FEEDER GROUP BUS M
CABLE VAULTS
ORIGINAL GROUPS A & B
NEW GROUPS A & B
ORIGINAL GENERATOR BAY
ORIGINAL GROUPS I-M-O
NEW GENERATOR & TRANSFORMER BAY
ORIGINAL GROUP U
ORIGINAL TRANSFORMER BAY
NEW GROUPS I & M

Figure 7. Thirteen-kilovolt switch house—longitudinal section

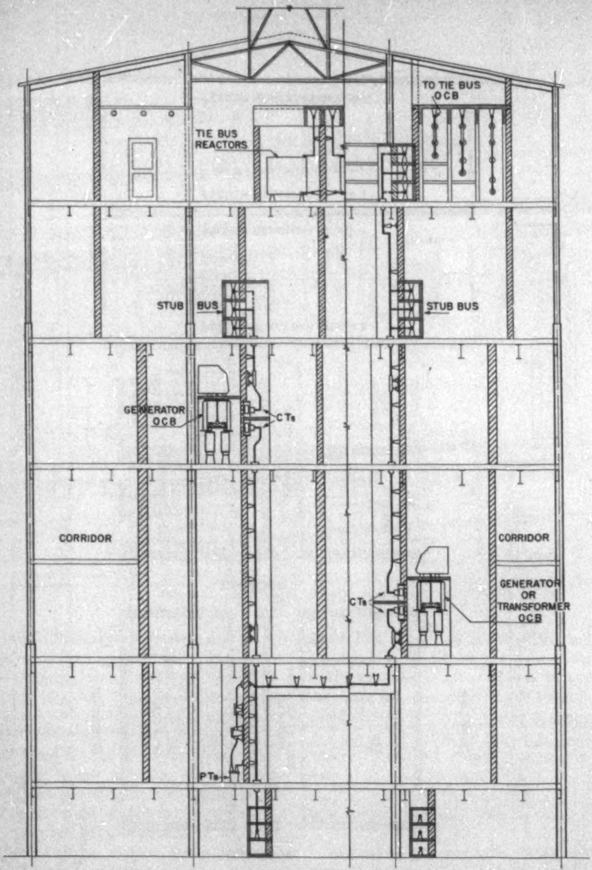


Figure 8. Thirteen-kilovolt switch house—composite cross section of generator and transformer bays

Each half contains a section consisting of two group busses with their generator, transformer, and tie-bus connections. Figures 7, 8, and 9 show the routing of the main and feeder connections and the segregation and arrangement of apparatus. As all oil circuit breakers, except the four for the tie bus, are located on the second and fourth floors, figures 8 and 9 were drawn as composite views, symmetrical about the center line, to include both floor arrangements. To make it possible to place each main oil circuit breaker in a separate room, two of each group were placed on the second floor, and the third on the fourth floor. It should be noticed that each of the four feeder groups, and the main supply leads for each group, are surrounded by barrier walls extending from the first to the sixth floor.

There are no doors or openings from any oil-circuit-breaker room to an adjacent room containing apparatus; access being provided only from the corridors. Smoke and flames, even in case the doors of a breaker room are blown off, cannot come in contact with other breakers or equipment without passing through a second door. All stair wells are enclosed to isolate each floor. All access doors are of steel, tight fitting, with spring-return hinges. The breaker room contains no other equipment, the connections from the breaker pots passing through the back wall of the cell into the lead compartment The rear walls of breaker rooms, and all walls separating adjoining apparatus rooms, are 12 inches thick, constructed of special concrete brick of tested characteristics. Walls of oil-circuit-breaker rooms on the longitudinal corridors are of eight-inch terracotta tile, in order to have less structural strength toward the corridors at the outside of the building than toward adjacent apparatus rooms.

The circuit breakers are the only oil-containing apparatus in the switch house. Potential transformers are of the dry type protected by fuses and resistors. A minimum number were used, and as their ratio is 13,200 to 110 volts, and they are wye connected, only 7,650 volts is impressed across the windings.

By using *FH*-129 oil circuit breakers, oil contents were reduced to the minimum. The total oil content of the 176 breakers in the old switch house was approximately 19,000 gallons, while in the new layout the 44 breakers located indoors contain 660 gallons.

Some of the oil circuit breakers formerly used contained 90 gallons per pole, while the largest present breaker contains 3 gallons per pot or 18 gallons total.

The main breakers are top connected and mounted on post-type insulators, gaining an advantage in that the forces incident to the closing operation are not taken by bushings surrounded by grounded parts.

Type *FH*-203 and *FH*-206 feeder oil circuit breakers of 350,000 kva and 500,000 kva interrupting capacity respectively, were reused, as the feeder reactors limit the duty of the breakers to much less than this value.

The four tie-bus breakers on the sixth floor are in separate rooms similar to those on the floors below. Segregation between the four group connections, equivalent to that on the lower floors, is obtained by corridors and the separating barrier walls. The connection to the outdoor portion of the tie bus, while not shown on any of the drawings included in this paper, passes down to the fifth floor in a separate room and then to the outside of the building, where it connects to the outdoor tie-bus leads on an overhead bridge.

The same general design of masonry cell and bus structure used previously and at Marion and Kearny generating stations, was continued in the new work; special concrete brick being used for vertical barriers and either precast or cast-in-place concrete for horizontal slabs. This construction has been found in the past to be effective as a barrier to stop the transmission of heat, from an arc or fire, to other equipment, it being found in several instances that equipment on the opposite side of an eight-inch wall from a fire or arc had not been damaged. Where practical, portions of the former lead and bus compartments were utilized.

All vertical leads, feeder and main, are insulated with 13/32-inch varnished cambric. Except for the back-connected stud of the feeder breakers, all leads, horizontal or vertical, through wall or floor tubes, are insulated. All floor and wall tubes are sealed with asbestos packing to prevent the passage of smoke from one room to another.

Main Leads

Generator and transformer leads are mainly single-conductor cable insulated with 18/32 inch of varnished cambric, covered with tinned shielding tape and a 6/32-inch rubber jacket, without an external braid.

Fire-Fighting Equipment and Provision for Smoke Removal

Owing to the small quantities of oil involved, 105 gallons, divided among the 42 pots of seven oil circuit breakers, being the largest amount contained in any one room, portable equipment was considered sufficient for extinguishing oil fires. Seventy-five-pound portable CO_2 extinguishers are located on each floor in sufficient number to produce a 50-percent CO_2 concentration in the largest oil-circuit-breaker room on each floor. Every oil-circuit-breaker room is provided with one or two small openings in the wall through which the CO_2 funnel may be inserted from the corridor and a cover closed to fit tightly around the pipe at the rear of the funnel. In this manner the CO_2 can be blown into the room without the use of the main access doors. As a second line of defense, special water-spray nozzles are provided which throw a finely divided spray or mist and use only a small quantity of water. The nozzles are permanently set so that a solid stream cannot be obtained, but the spread of the spray is adjustable from approximately 30 to 150 degrees.

Three portable two-inch rubber hoses are provided on each floor, each with a $1^1/_2$-inch spray nozzle permanently attached, and so located that at least two are available for each oil-circuit-breaker

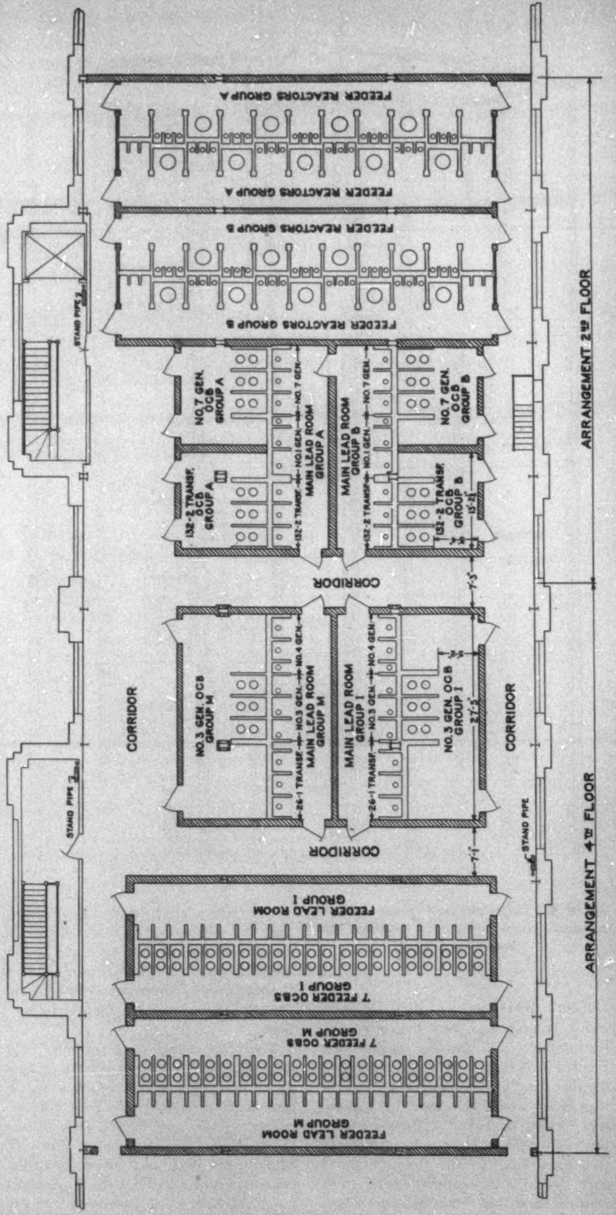
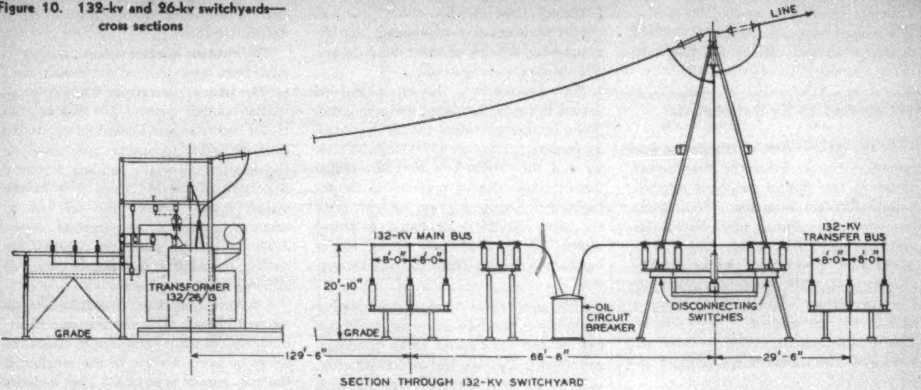
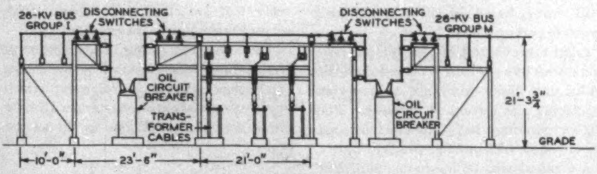

FEEDER REACTORS GROUP A
FEEDER REACTORS GROUP A
FEEDER REACTORS GROUP B
FEEDER REACTORS GROUP B
STAND PIPE
NO.7 GEN. OCB GROUP A
NO.7 GEN.
NO.1 GEN.
132-2 TRANSF.
MAIN LEAD ROOM GROUP A
MAIN LEAD ROOM GROUP B
NO.7 GEN. OCB GROUP B
132-2 TRANSF. OCB GROUP A
132-2 TRANSF. OCB GROUP B
15'-2"
CORRIDOR
7'-5"
ARRANGEMENT 2ND FLOOR
CORRIDOR
NO.3 GEN. OCB GROUP M
NO.4 GEN.
NO.3 GEN.
26-1 TRANSF.
MAIN LEAD ROOM GROUP M
MAIN LEAD ROOM GROUP I
NO.3 GEN. OCB GROUP I
27'-5"
CORRIDOR
STAND PIPE
CORRIDOR
7'-1"
STAND PIPE
FEEDER LEAD ROOM GROUP I
7 FEEDER OCBS GROUP I
7 FEEDER OCBS GROUP M
FEEDER LEAD ROOM GROUP M
ARRANGEMENT 4TH FLOOR

Figure 9. Thirteen-kilovolt switch house—composite second- and fourth-floor plans

Figure 10. 132-kv and 26-kv switchyards—cross sections



SECTION THROUGH 132-KV SWITCHYARD



SECTION THROUGH 26-KV SWITCHYARD

room. These spray nozzles may be inserted in the above mentioned hand holes in the same manner as the CO_2 funnels.

By installing a raised saddle at the bottom of each access door, a two-inch sill is obtained which is sufficient to keep oil from flowing from the floor of the breaker rooms out into the corridors. This sill also will assist in holding water from the spray nozzles in the rooms.

Previous to this rebuilding program, the 3,750-kva station auxiliary power transformers, housed in a section of the building adjoining the switch house, were equipped with a permanently piped foam system with a foam generator. All smaller indoor auxiliary power and lighting transformers have been replaced with transformers filled with noninflammable fluid.

Fire hydrants, connected to the city fire mains, are located at strategic points in the three outdoor yards so that all breakers and transformers may be easily reached with portable hoses equipped with the large spray nozzles supplemented by fog nozzles mounted on a 90-degree elbow with a 15-foot aluminum extension.

Fans are located in the outside east wall of the building on each oil-circuit-breaker and reactor floor in sufficient numbers to clear the corridors of smoke and fumes. Previous experience has shown that these fans are effective, and it is expected, particularly in view of the small quantities of oil contained in any one room, that the corridors will be sufficiently cleared of smoke to permit access to the small fire-fighting openings. The fans are controlled from a remote location.

Interlocks

Interlocks of the key type prevent the opening or closing of isolating disconnecting switches when the oil circuit breaker is in the closed position. In the case of stick-operated disconnecting switches, the locks are applied to the compartment doors.

Grounding

Grounding of apparatus and equipment in the indoor switch house is accomplished by a grid system consisting of four-inch by one-fourth-inch copper bars tied together so that the effective cross section between any piece of apparatus and ground is at least two square inches. All apparatus is grounded to this grid, the oil circuit breakers being grounded at two points. The double grounding of breakers and the two-way flow in the grid makes it possible to have a poor connection at any one point and still retain good grounding conductivity and capacity. Likewise, the grounding of all of the outdoor switchyards consists of a similar grid system. Cable ties totaling 2,500,000 circular mils cross section connect the 132-, 26-, and 13-kv outdoor and 13-kv indoor grounding systems.

Neutral Grounding Systems

The neutrals of the 13-kv generators were previously grounded through a two-ohm resistor of one-minute thermal capacity. As overheating troubles with the neutral resistors had occurred when a ground did not clear quickly, additional precautions were thought to be necessary to make absolutely certain that in case of any failure of the protective devices to function, the system would not be ungrounded by the burning out of the resistors. The continuous capacity of this two-ohm resistor is 450 amperes. As replacing it with a continuous-capacity resistor good for the 3,800 amperes which would be obtained by full phase-to-neutral voltage being maintained across the resistor was impractical on account of the space occupied and the excessive cost, a 12.9-ohm resistor of 450 amperes continuous duty was installed, normally short-circuited by a single-pole oil circuit breaker. A timing relay actuated by the ground current opens this breaker if ground current flows for 30 seconds, and the total of 14.9 ohms reduces the current to 450 amperes, the continuous capacity of both resistors. The 132-kv system is dead grounded, while the 26-kv system is grounded through a 75-ohm resistor which has an oil circuit breaker actuated by a timing relay, so that in case a ground does not provide sufficient current to operate the protective ground relays, the resistor is shunted, giving additional chance for the automatic clearing of the ground fault.

132-Kv and 26-Kv Switchyards

As the greater part of the future load growth will be carried on the 26-kv busses, a site on the station property, approximately 900 feet from the switch house, was selected, providing space for an ultimate of six 132-kv lines, four 132-to-26-to-13-kv transformer banks, and if necessary, 40 26 kv feeders, divided into four two-group sections in a manner similar to the indoor 13-kv scheme. This site permitted a well-balanced design, with the transformers between the 132-kv and 26-kv portions, and placed the 26-kv feeders close to the duct lines entering the property and thus relieved the duct congestion adjacent to the switch house.

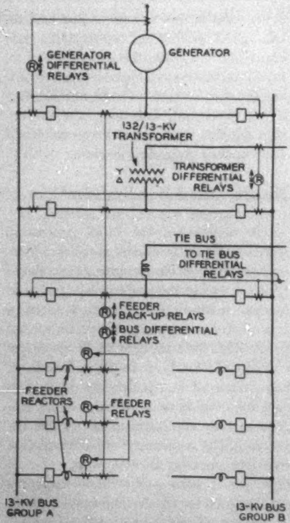


Figure 11. One-line diagram—13-kv group-bus relay protection

The 132-kv layout is of the ground-bus A-frame type, a standard for the switching stations on the Public Service Electric and Gas Company's system.

In the 26-kv portion, the general structure has been lowered in height and spread out more than the standard 26-kv layouts previously used, to remove any busses and disconnecting switches from locations immediately above the oil circuit breakers and approaches the flat ground-bus scheme of the 132-kv design. This is shown on figure 10.

For the present, the equipment as shown in figure 2 suffices, one two-group 26-kv section providing for the seven 26-kv feeders. The two 45,000-kva 132/13-kv and the 50,000-kva 26/13-kv transformer banks existed previous to the rebuilding. Connected as shown, with the new 132/26/13-kv bank, a power source to all 13-kv and 26-kv feeder busses is available from the 132-kv system.

This new three-winding transformer bank has a continuous rating of 50,000 kva on the 132-kv and 13-kv windings, and 60,000 kva on the 26-kv winding, with 33 per cent overload capacity with forced air cooling. An additional overload rating, based on the system's load cycle, is also available.

Load ratio control of plus ten per cent and minus five per cent is provided on the 13-kv and 26-kv windings, to assist in regulating the three bus voltages. The 132-kv windings have standard no-load tap changers with one five-per-cent tap.

A-c calculating-table studies indicated that the above kilovolt-ampere ratings and range of voltage regulation formed the best economical balance for the results desired.

Control

Partly due to the distance between the 132-kv and 26-kv switchyards and the switch house; and partly to the desire for segregation, two separate control rooms were decided upon, one located in the switch house for both indoor and outdoor 13-kv sections, and the other in the center of the 132-26-kv switchyard for the remaining apparatus.

The 13-kv control room is located in the end of the switch-house building, toward the outdoor 13-kv switchyard, in a section separated from the switching equipment. This location permitted the control from the indoor and outdoor 13-kv sections to enter the conduit room at opposite ends; the indoor, from the adjacent switch galleries, and the outdoor, from a shaft built into the end wall of the building. The control board is divided into an indoor and outdoor section, running longitudinally, on opposite sides of the room, so that the controls from the indoor and outdoor sections can be racked on opposite sides of the room, without any crossovers or congestion. The new control room is larger than the previous room, and with less than half the circuits to control, the spacing and segregation is greater.

The outdoor control is run in armored cable from the bottom of the vertical shaft to the panels, racked in metal troughs in the conduit room. The indoor control is run from the individual apparatus in rigid conduit to conduit galleries along the outside wall of the building, formerly a portion of the old third floor of the switch house, where they are run in armored cable to the conduit room. Additional segregation is obtained by routing the control of alternate groups to opposite conduit galleries.

Trip-coil supervision is obtained on all oil circuit breakers by means of an indicating lamp, which is energized in either the closed or open position of the breaker, if the trip circuit is intact. This includes the breaker trip coil and auxiliary switches, relay test switches, and all protective relays that may trip the breaker.

The same precautions in segregation of control have been exercised in the design of the new outdoor control room, which operates on a separate battery with only minor control connections to the switch house.

Protective System

Differential protection consisting of type *CA* and *CA*-4 relays, with the current transformers overlapping, is used on all apparatus and busses, so that there are no unprotected spots. Current trans-

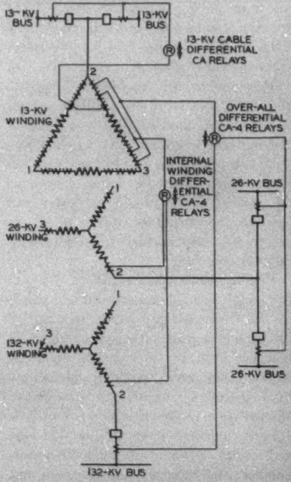

13-KV BUS
13-KV BUS
13-KV CABLE DIFFERENTIAL CA RELAYS
2
13-KV WINDING
1
3
OVER-ALL DIFFERENTIAL CA-4 RELAYS
INTERNAL WINDING DIFFERENTIAL CA-4 RELAYS
1
26-KV WINDING
3
2
26-KV BUS
1
3
132-KV WINDING
2
26-KV BUS
132-KV BUS

Figure 12. One-line diagram—three-winding transformer-bank relay protection

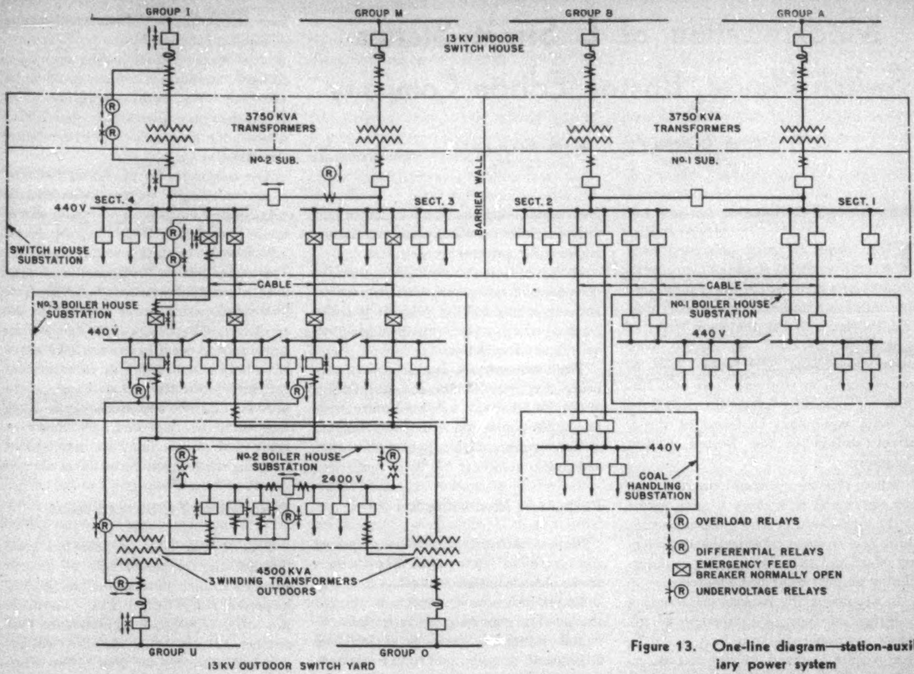

GROUP I
GROUP M
13 KV INDOOR SWITCH HOUSE
GROUP B
GROUP A
3750 KVA TRANSFORMERS
3750 KVA TRANSFORMERS
NO.2 SUB.
NO.1 SUB.
BARRIER WALL
440V
SECT. 4
SECT. 3
SECT. 2
SECT. 1
SWITCH HOUSE SUBSTATION
CABLE
CABLE
NO.3 BOILER HOUSE SUBSTATION
440V
NO.1 BOILER HOUSE SUBSTATION
440 V
NO.2 BOILER HOUSE SUBSTATION
2400 V
440 V
COAL HANDLING SUBSTATION
4500 KVA 3 WINDING TRANSFORMERS OUTDOORS
GROUP U
GROUP O
13 KV OUTDOOR SWITCH YARD
R OVERLOAD RELAYS
R DIFFERENTIAL RELAYS
EMERGENCY FEED BREAKER NORMALLY OPEN
R UNDERVOLTAGE RELAYS

Figure 13. One-line diagram—station-auxiliary power system

formers in the same protective zone were purchased with matched characteristics and tolerances limited up to the maximum through short-circuit current values.

Feeder reactors limit the current on feeder faults to a value well within the capacities of the breakers. With the current transformers located as shown in figure 11, the feeder relays do not function on faults between the reactor and breaker, a fault so located being cleared by the bus differential relays. A 36-cycle time delay is interposed between the tripping of the main source relays and the feeder relays, so that in no case do the feeder breakers interrupt the bus short circuit. To provide back-up protection for the feeder breakers, the source differential-current transformers are summarized through three *CO* overcurrent relays before reaching the bus differential relays, so in case a feeder oil circuit breaker fails to open, the group bus will be cleared.

A spare oil circuit breaker and transfer bus are included in the 132-kv switchyard to replace any regular breaker. For all replacements except when used for the bus section breaker between sections 3 and 4, the bus differential is maintained by transfer of secondary control circuits.

The new three-winding transformer has three sets of differential relays, as shown in figure 12, consisting of an "internal" for winding protection, an "over-all" for 132-kv and 26-kv leads and bushings, and a "cable" differential, for the 13-kv cables. This has been found desirable due to the difficulty experienced in phasing and testing a single over-all differential on a three-winding bank where one winding is delta connected. An added advantage is that the internal protection remains intact during any switching changes necessary when the spare oil circuit breaker is used.

Auxiliary Power

The existing auxiliary power system consisted of a four-section 440-volt bus with nonautomatic section breakers, without smoke or fire barriers to isolate the various sections. This bus was divided into two parts, as shown in figure 13, with a barrier wall between, and the cables rearranged so as to have no interconnections between the two halves. The two sections of each half are joined by a tie oil circuit breaker with overcurrent relays set so that in case of a 440-volt bus fault, the two sections will be separated before the overcurrent back-up relays on the transformer breakers operate. It was not feasible to install bus differential protection on the existing busses. Cables between the main auxiliary substation and the boiler-house substations are equipped with differential protection and overcurrent back-up protection to clear bus faults.

To supply the auxiliaries of the new turbine generator and boilers, a new boiler-house substation, No. 2, was installed. Differential relays protect the two sections of the 2,400-volt metal-clad bus which are separated by a barrier wall. This bus is fed by two new 4,500-kva 13-kv to 2,400-volt to 440-volt transformers connected to two of the outdoor 13-kv groups. The 440-volt windings provide an additional power source to a portion of the existing 440-volt bus. The auxiliary power system will normally operate in three parts; sections 1 and 2 and No. 1 boiler-house substation, fed from indoor groups *A* and *B;* sections 3 and 4, fed from indoor groups *I* and *M;* and Nos. 2 and 3 boiler-house substations fed from outdoor groups *O* and *U.*

With this division, faults on the 440-volt and 2,400-volt busses can only shut down a portion of the auxiliaries. In addition, duplicate essential auxiliaries, wherever possible, were reconnected to obtain their supply from different bus sections.

Conclusions

In the reconstruction of Essex generating station, no unique or unusual apparatus or design features were used. Rather, with part existing equipment, new commercially available apparatus, and refinements in standard designs of structures, a plan was developed which it is believed will provide a high order of reliability. Emphasis was placed on separation and segregation as a second line of defense to stop the spread of a conflagration. In striving toward more reliable future designs, circuit breakers without inflammable fluid would be of most assistance. With concentrations of large blocks of power, safe back-up protective schemes are desirable in addition to bus and apparatus differential, and more sensitive transformer protection would be welcomed. In an attempt to obtain the latter, it is intended to make a trial installation of the so-called "gas relays" on the transformer banks at Essex generating station.

Discussion

For discussion, see page 778.

Modernization of L Street Station Switch House, Boston Edison Company

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Purpose of This Paper

THIS paper is being presented with several objects in view, to serve possibly as a guide or outline of procedure for companies undertaking a modernization program, to list the main items of equipment installed, to discuss why certain selections were made, and to aid engineers in studying their own stations by indicating dangerous conditions or weak equipment as found at the L Street station of the Boston Edison Company.

Where type numbers and manufacturer are mentioned it is done to give credit to the manufacturer who produced something new or spent considerable engineering effort and to aid the reader in determining quickly what was adopted.

In discussing the reasons for adopting a system or type of equipment no attempt has been made to indicate the relative weight assigned to the factors involved. Obviously the final conclusions even considering the same factors would vary for different systems and conditions, engineering preferences, etc.

It is particularly desirable to invite discussion of this paper as the comments and suggestions will be valuable to those contemplating a modernization program as well as to ourselves.

The switch-house modernization is being accompanied by the installation of a 37,500-kva topping unit with two 1,200-pound pulverized-coal boilers, a description which appears in other articles.

Purpose of Modernization

Modernization as applied to a power station is a modern term but the principles are as old as the station itself.

Engineering with respect to power stations has gone through various stages—first it was a question of building larger and larger power units—then it was economy at any cost—this was followed by recognition that fixed expenses are important—and now we have modernization expressing itself in segregation.

There are several reasons why this subject has recently attracted such interest. Many of the older and larger stations have reached an age where much of the equipment has outlived its usefulness. Several cases of troubles and fires have focused attention on the question of electrical and physical segregation. The depression gave a breathing spell which allowed the engineers to look over their stations.

The adoption of a modernization program sometimes requires considerable courage as the expected results are somewhat intangible. There may be no or little increase in station load or capacity. The actual service to the customer may not be materially bettered as the past history of continuity of service may be excellent. Often there is no definite circumstance to point to as there may never have been a serious fire or electrical disturbance. On the other hand, there isn't any station but which has features that could be improved. Obviously, a great deal of care must be exercised in selecting the program to be followed.

Description of L Street Station

This station built in 1898 has gone through the various stages of growth common to such stations and has reached its present size of 210,967 kva. The addition of a 37,500-kva high-pressure unit number 12 now being installed will increase this to 248,467 kva. The seven 14-kv units were connected to a double ring bus which was divided by the breakers into four sections. The outgoing lines, tie lines, station transformers, etc., totaled 68 cell positions and were distributed along the ring bus.

Each 14-kv generator has a four-ohm neutral resistor and circuit breaker, one only being in service at a time.

The electrical equipment per line is located on three floors—reactors and ducts on first floor, busses on second, and oil circuit breakers on the third. The fourth floor was empty. The switch house is in two connecting buildings, but in general there was practically no segregation between main and auxiliary busses or between bus sections.

Preliminary Studies

Due to the increased generating capacity and to tie lines with Edgar generating station and with New England Power Company the calculated short-circuit fault current far exceeded the ratings of many of the oil circuit breakers. Several years ago a study was started for increasing the rupturing capacity of these breakers. These are General Electric type *H* breakers and

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vary from the original design to the more recent installations. It would have been quite expensive to modernize or replace these breakers to meet the required rupturing capacity since the ring bus is normally operated closed and there are no bus sectionalizing reactors.

The next scheme studied called for a synchronizing bus with reactors connected to each of the four bus sections. As the bus tie breakers could now be normally opened the short-circuit duty per bus section would be very materially reduced. A bus fault should shut down only one-fourth of the station instead of the whole bus. Also the voltage disturbance of the sections not in trouble would be much less.

Electrically this layout was decidedly an improvement but due to the arrangement of busses and breakers in the switch house the modern principles of segregation could not be applied effectively.

This led to a proposal providing for an entirely new and separate switch house having main and auxiliary busses divided into four sections. These sections would be tied together through reactors and a synchronizing bus although bus tie breakers would be installed for load transfer purposes at light loads or in emergencies (figure 1).

Each section would have the switching equipment for two generators which would be transferred from the present bus and would also have switches for a group feeder tie connected to the present corresponding line bus section. The tie breakers between the line sections would be removed and installed between generator bus sections.

Partition walls would be installed between sections of the generator busses and between sections of the present line busses so that electrically speaking the station would be divided into four groups each consisting of a double-bus generating station with two generators and feeding a double-bus substation with the various transmission lines. The advantages of having the generating switching equipment in a switch house incorporating the newer principles of construction were considered to be of sufficient importance to warrant the increased cost over the preceding scheme. These features will be discussed in detail later on.

There were three locations considered for the generating-bus switch house.

A new building would have given complete separation from the present switch house, but the cost was excessive and the space available was somewhat limited.

Space was available in the engine room or boiler room of a building which had recently been cleared of equipment. This would have given good segregation from the rest of the station and the cost would have been reasonable as the building, floors, and foundations are in good condition. Use of either of these rooms, however, would have seriously interfered with possible use of the building as a future boiler and turbine station. The biggest disadvantage was the problem of running the generator and group feeder leads between this and the present station. Based on statistical records the expected faults with lead cables and potheads would have been entirely unacceptable for a generating station. Insulated cable mounted on porcelain insulators would have required a tunnel or overhead enclosed bridge either of which would have been very expensive as well as having the danger of shutting down the entire station in case of a serious fault or fire, earthquake, air raid, or sabotage.

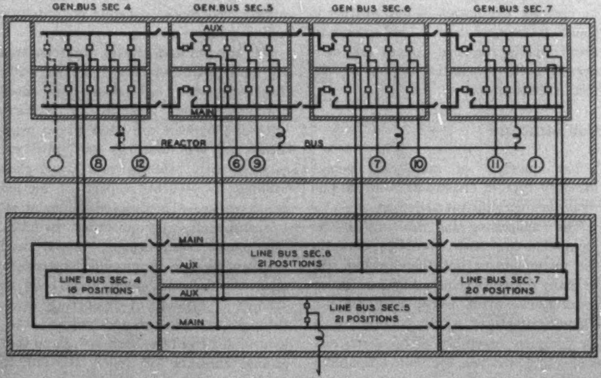


Figure 1. Single-line diagram—generator and line bus sections

The necessary additional space was secured by using the unoccupied fourth floor of the present switch house. This floor is entirely sealed off from the rest of the building and can be entered only by outside stair wells. The headroom is somewhat small and introduced serious problems but the width is ample and the length is right.

Switch-House Design (Figures 2 and 3)

The only building work required was to close in a skylight, brick in a few windows, and install two doors connecting to the stairs by outside walkways of fire-escape construction. The strength of the floor was checked to insure it was suitable for the weight of the additional switching equipment and cell construction.

In line with the principles of physical separation it was decided to locate the switching equipment for the four bus sections in individual rooms separated by five-foot aisles. These aisles serve as safety exits since workmen leaving a bus section in trouble do not have to pass through other section aisles. The doors swing outward into the aisles and are equipped with door closers. A fire or explosion in a bus section might swing open or blow off a door but fire being forced into other bus rooms is improbable as their doors would be tightened against their jambs and as the aisles act as expansion chambers. The doors are equipped with wire-glass windows to permit inspection without the operator entering the room.

Each room is divided longitudinally into four aisles—one for the main bus and disconnects, one for auxiliary-bus disconnecting switches, and instrument transformers, and two aisles for the main and auxiliary oil circuit breakers. The bus structure and breakers cells are of reinforced concrete. All other walls and partitions are two-inch walls having a metal lath specially reinforced and three coats of plaster on each side.

Fire Protection—Gas (Figure 4)

A CO_2-gas Lux fire-protective system is installed with thermostats to operate an annunciator or to discharge into the particular aisle in trouble. Manually operated selector valves and a bank of reserve gas cylinders are also available.

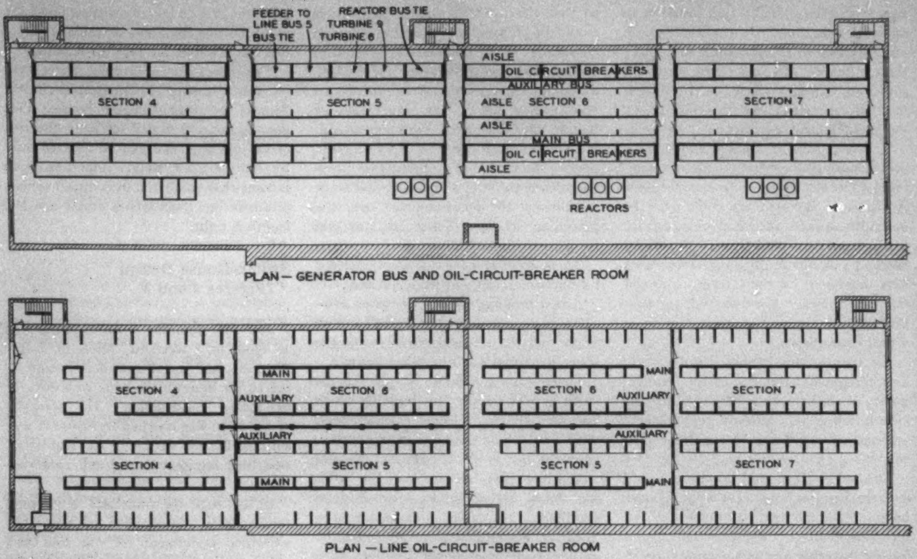

FEEDER TO LINE BUS 5
BUS TIE
REACTOR BUS TIE
TURBINE 9
TURBINE 6
AISLE
OIL CIRCUIT BREAKERS
AUXILIARY BUS
SECTION 4
SECTION 5
AISLE SECTION 6
SECTION 7
AISLE
MAIN BUS
OIL CIRCUIT BREAKERS
AISLE
REACTORS
PLAN — GENERATOR BUS AND OIL-CIRCUIT-BREAKER ROOM
MAIN
SECTION 4
SECTION 6
SECTION 6
SECTION 7
AUXILIARY
AUXILIARY
AUXILIARY
AUXILIARY
MAIN
SECTION 4
SECTION 5
SECTION 5
SECTION 7
MAIN
MAIN
PLAN — LINE OIL-CIRCUIT-BREAKER ROOM

Figure 2. Plan—generator-bus and line-circuit-breaker floors

Fire Protection—Water

There is also a system of eight Los Angeles water fog nozzles installed for each aisle. The 16 feeder pipes are brought out into the stair wells to a six-inch header, the connections being made through short lengths of removable hose normally disconnected as an aid to the operator in insuring selection of the right valve. As a further check there is a set of indicating lamps at the valves—one to show if the bus is alive, one to indicate a bus-differential—relay operation, and one to be operated by the switchboard operator. Hose and reels with portable fog nozzle applicators are provided for mop-up work.

The fog type of nozzle was selected in preference to the spray type as it was felt that the fog would more readily roll behind the cell doors and around the apparatus and wiring within the cells or bus structure. The nozzles are located in front of alternate cell barriers and tests indicate both cells are well filled when 100-pounds water pressure is at the nozzles.

It is intended to rely on the city fire-department pumper to supply the six-inch header; however, the system can be connected to the 60-pound city water supply. As all hose connections correspond to the Boston fire department it can supply directly the individual aisles or the portable applicators.

Each aisle has suitable drains and a four-inch dam at each end.

Ventilation (Figure 5)

Two exhaust fans are mounted on the roof. Separate ducts with manually operated dampers are run at one end of each aisle. An automatic louver is mounted above the door at the other end of the aisle. After a fire the proper damper can be opened and the aisle scavenged of smoke. This system may also be used for ventilation in hot weather if found to be necessary. The aisles and area outside the bus rooms are connected to the ventilating system for the rest of the station.

Cell Structure

The question of metal-clad versus masonry type of construction in the bus rooms is quite difficult to decide.

The engineering and drafting for the metal-clad equipment would be done by the manufacturer but there would still be many drawings required to show interconnections, main leads, and control. The manufacturer would be responsible for complete assembly of breakers, disconnecting switches, etc., but assembling the units, lining up, and making main and control connections would still have to be done in the field. Quotation on the metal-clad would be independent of possible future labor troubles or price increases. Flexibility and ease in relocating equipment in the future are not of much moment as such a change is not expected and as the cost of interconnections, main and secondary wiring, etc., would have to be written off in either case. In the metal-clad construction the individual-phase equipment and conductors are surrounded by metal so that most faults should be ground faults. This is a very important point, but it is believed that the equivalent has been approached in the concrete construction adopted (figure 6).

All circuits and phases are separated by metal lath and plaster barrier walls. Ebony-asbestos cell doors are used throughout and Transite or Micarta enclosing barriers are used where practical. All wall bushings and tubes are packed with asbestos and water-glass stuffing to prevent seepage of ionized gas or smoke. The bases of all insulators, bus supports, disconnecting switches, instrument transformers, fuses, and breakers are directly grounded by copper strap so that flashovers should be to ground. Equipment-supporting steel, through conduit, ground copper, etc., is insulated from the barrier walls so that ground currents will follow the ground copper and not the building or wall steel. Reinforcing rods in the concrete were spaced at the ends and were taped at crossings to prevent ground currents as well as possible circulating currents. An attempt was made as far as possible to keep reinforcing rods a good distance from busses or heavy currents. Care was taken to prevent possible metallic loops of supporting steel or reinforcing rods around current-carrying parts. It is realized that there are a few spots where heavy conductors are somewhat near building steel and they will be watched and remedies made if found necessary.

Due to the low headroom there are a few places where exposed live parts are only a few inches from concrete. In such cases the cell was lined with one-fourth-inch Micarta barriers.

Gang-operated disconnecting switches in a metal-clad switchgear are somewhat safer as they can be enclosed and remotely operated but the cell type of construction offers the advantages of visibility for the individual blades and of better separation from the bus. A green indicating lamp is being installed at each set of disconnects to indicate the open position of the associated circuit breaker but main reliance will be placed in the "tag-out" procedure.

In the metal-clad gear interlocks either mechanical or key type can be installed between the breakers, disconnecting switches, and cell doors, but their desirability may be mitigated somewhat by the possibility of giving the operators a false sense of security. Interlocks are valuable for small substations or industrial switchgear installations but are not essential for large generating stations having highly trained operators accustomed to rigid operating procedures.

It must be kept in mind, however, that notwithstanding the above apparently unfavorable comments the idea of factory-assembled switching equipment is good and the Boston Edison Company has many installations in the generating and substations as well as in customers' stations. In this particular installation the estimated saving of the cell type over the metal-clad was too great to be disregarded.

Oil Circuit Breakers

The release of the type *H* generator and bus tie breakers from the line bus forced the new structure design to be suitable for this type of breaker. This was acceptable as the record of the type *H* breaker over the whole life of the station has been exceptionally good, and as their oil contents are relatively small. Before reinstalling these breakers they are modernized and brought up to 1,000,000-kva rupturing capacity and 23-kv insulation by adding new explosion chambers, 45 degrees silver contacts, new insulators, etc. As the subcell disconnecting switches could not be used in the new layout the breakers were changed to be top connected.

Because of several instances of pumping due to breakage of dogs or stops in the mechanism it was decided to add an antipumping interlock.

The use of bus selector breakers only introduced operating and synchronizing difficulties but the cost of a series breaker could not be justified.

Nine new *FH*126 breakers with motor-operated mechanisms were installed to supplement the relocated breakers.

Bus and Cell Structure

The main and auxiliary bus structures consist of horizontal reinforced-concrete shelves with removable Transite front covers except at bus taps. All of this concrete was mechanically vibrated while being poured to obtain a more homogeneous structure. As the expected short-circuit current is fairly small (20,000 amperes) the magnetic

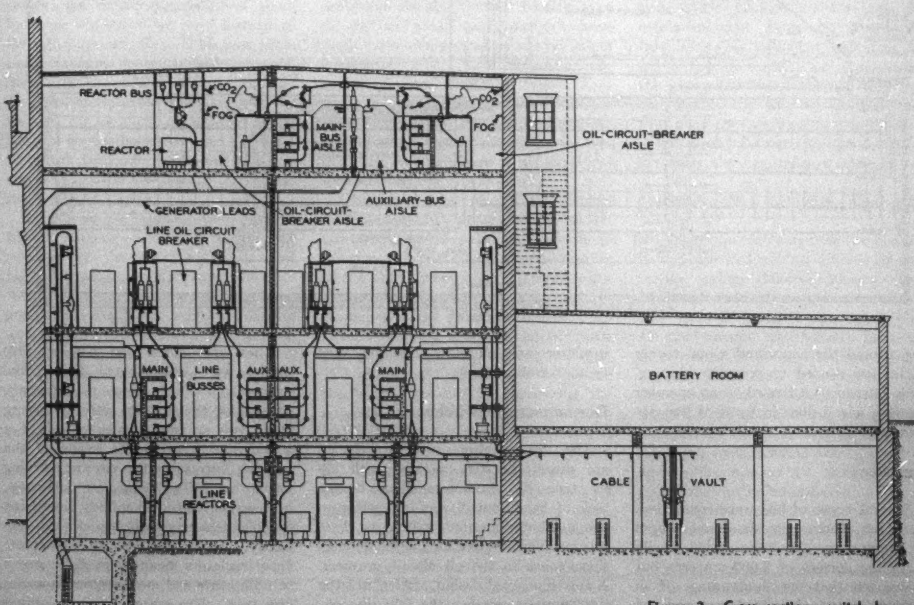


Figure 3. Cross section—switch house

forces between phases are not large. It is not felt that the longitudinal forces tending to strip the bus through the end clamps are serious.

All cells are equipped with removable hanging doors. The design of the cell doors has an unvarnished one-fourth-inch black ebony asbestos panel with a wooden frame impregnated with fire resistant paint. Various materials were considered but the above was selected as it is fireproof and will not glow, it is strong mechanically, will not absorb moisture or warp, does not give off excessive fumes or smoke during a fire, and being homogeneous it may still be serviceable after grooves or scorched parts are sandpapered out. There are several materials available which do not require a frame, but usually a binding around the edges and metal corner plates are needed to prevent chipping. This introduces a hazard to an operator hanging a cell door in front of live apparatus.

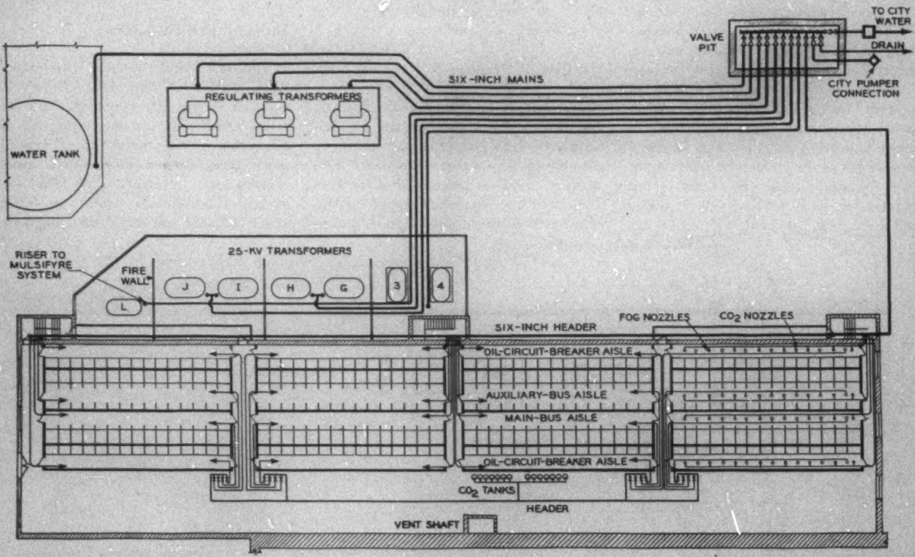
Busses

Several types of bus were considered. Bare bar, tubing, or structural shapes of copper or aluminum could easily carry the current of 3,000 amperes but it was felt that the disadvantage of an insulated bus in increased cost and the possibility of fire and smoke was well outweighed by the advantage of an insulated bus in reducing flashovers caused by dirty or broken insulators, rodents, or ionized gases.

Two 3,000,000-circular-mil insulated cables per phase mounted on 23-kv insulators were selected for main and auxiliary busses as this was materially cheaper than copper bar or tubing having formed or wrapped insulation. Vertical bars to give good ventilation would have introduced serious difficulties in making taps as the headroom was limited.

Similarly, all bus taps and cell wiring are insulated cables mounted on 23-kv insulators with all joints filled and taped to a streamline shape.

Figure 4. Fire protection system—transformers and switch house

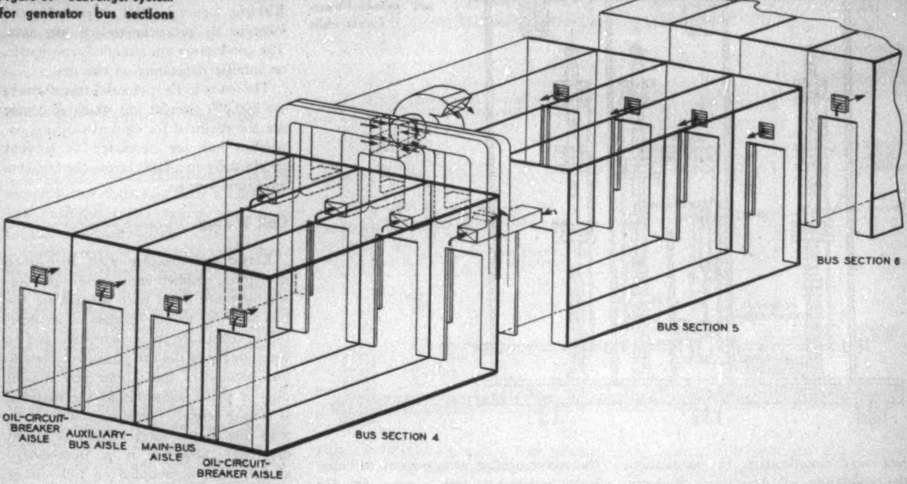


Disconnecting Switches

The disconnecting switches selected are single-pole stick-operated with 23-kv type *B*-3 insulators. Due to the lack of headroom it was impossible to use a front-connected switch as there was insufficient space for the top connections going to the oil circuit breakers. A rear-connected design particularly the 3,000-ampere size has the following objections: Any undue strain in service or during erection tending to turn the through stud as might be caused by the weight of cables or by a mechanic putting too much force on the nuts would cause misalignment. Similarly, any expansion of the stud due to temperature might loosen the assembly and cause misalignment. The terminal-stud passage through the insulator is not ventilated and the temperature of the stud is increased. The temperature of the contact clips would tend to be increased due to the distortion of the current distribution by the magnetic action. There is also danger of corona between the switch stud and the inside of the porcelain bushing. Due to the right-angle path of the current the forces on the switch lock are materially increased during short-circuit conditions.

These mechanical and heating difficulties were compensated for in the proposals of the various manufactures by pinning the studs to prevent turning using two or more straps instead of a round stud, coating the inside of the bushing, increasing the current-carrying parts, etc. The Delta-Star company, however, developed an entirely new design for disconnecting switches of this capacity. This switch consists of two post-type insulators mounted at right angles to each other and mounted on an angle-iron base. The switch blade is located

Figure 5. Scavenger system for generator bus sections



across the two outer ends of the insulators. The terminal blocks can be rotated for the connections to be to the front, in line, or to the rear at either top or bottom stud. Obviously, such a design offers the advantages of a front-connected switch, the interchangeability is good, bus-type insulators are used instead of through bushings, there is no base plate to have possible heating by eddy currents, installation is cheaper as two switches per phase are mounted on an angle at the factory, the problem of accurate alignment of supporting steelwork to prevent distortion does not exist, and the first cost is materially less than for equivalent rear-connected switch.

Area type of contacts using double blades gripping a central tongue was selected over the line type as it was felt the latter is more sensitive to accurate adjustment. As an extra precaution, however, the contacts are somewhat flexible and pressure is maintained by a central spring washer.

The contacts are silvered, not with the intention of increasing the capacity of the switch but with the expectation of prolonging the life of the contacts.

A bar type of lock was selected as it was felt a latch on a round stud might wear and become ineffective.

Current and Potential Transformers

The present generator current transformers will be used in the new structure. These are 15 kv whereas all the rest of the equipment is on the 23-kv basis; however, these transformers are within the generator differential protection and the cost of new ones was not felt to be justifiable.

The current transformers used for bus protection are new General Electric type *KC*-59*Y* and are of special design to have good ratio characteristics during fault conditions.

New General Electric type *JE*-41 dry-type potential transformers, 13,800/-115-volt insulation, are installed one per generator for synchronizing and three per bus section (main and auxiliary) for metering and synchronizing.

Connecting the generator potential transformer from phase to ground retains the phase segregation principle in the structure and allows the transformer to operate at 8,000 volts. Theoretically a potential transformer connected to ground with the generator neutral open as an incoming machine might cause neutral shift and unbalanced voltages. This effect could be overcome by closing the neutral breaker by connecting the potential transformers to generator neutral instead of to ground, connecting it phase to phase, or installing two potential transformers phase to ground but these schemes have the objections of being more complicated, costing more, destroying phase segregation, or operating at 13,800 instead of 8,000 volts.

The generator manufacturer, however, feels that the above voltage distortions will not take place as there is a 90-ohm resistor in series with potential transformer. Star-connected bus potential transformers also work in better with the rest of the station relaying.

Each potential transformer is protected with a Schweitzer and Conrad combination 23-kv 90-ohm resistor and disconnecting-type boric-acid fuse. The fuse itself has sufficient rupturing capacity but the resistors aid in preventing the above-mentioned voltage distortion, they reduce the duty on the fuses, and they allow the bus fuses to blow in case of potential-transformer troubles instead of involving the high-voltage relaying.

Generator-Bus Relaying (Figure 7)

Each of the four generator-bus sections have phase and neutral differential protection using General Electric type *IAC*11*E*4 and *E*44 relays respectively. The bus tie breakers are overlapped. All the current transformers have the same ratio 3,000/5 or 1,500/2.5 depending on the circuit capacity. As the short-circuit current is only six or seven times the rating and as the transformers are specially designed and the relays are set above load currents there should be no troubles due to d-c components or transformer-ratio breakdown.

Due to the special design of current transformers, no serious leakage of current is expected through the paralleled secondaries of the current transformers.

The fault-bus system of protection was not selected because of the increased

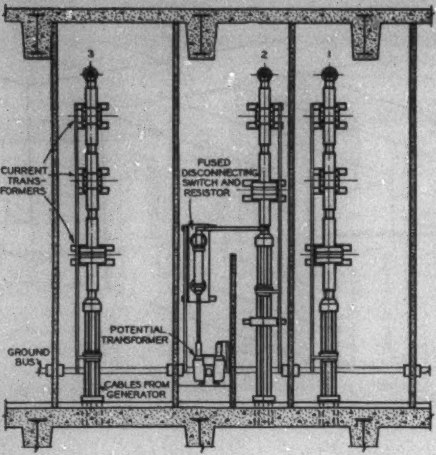


Figure 6. Current- and potential-transformer cells

cost and complication of installation, the possibility of stray fault currents, and the undesirability of not having equipment definitely grounded.

The reactor bus including reactors and leads are similarly differentially protected.

The group feeders have overload back-up protection with long time setting. Type *IAC* relays are used.

Each generator has differential protection which trips the bus breakers, neutral breaker, field switch, throttle trip, and CO_2 gas (last item for number 12 unit only).

Cables

The insulation selected was 23/64-inch varnished cambric (about 22-kv rating) with a copper shielding tape, 6/64-inch rubber jacket, and a fireproof-weatherproof braid. The present generator leads are not shielded but they have 23-kv insulation and a hose jacket. In order to reduce possible corona and to prevent electrical shock it was decided to shield the new cable. A grounded sheath will cause a positive relay operation on an insulation failure whereas an ungrounded sheath may allow a fault to simmer along until a serious disturbance occurs. The switch house is normally dry but the rubber jacket was added as a precaution against condensation or possible water during a fire.

A typical group feeder or generator has three conductors per phase and are arranged in three three-conductor duct banks. Here again the manufacturers and published data varied considerably in the recommended arrangement to cause least unbalance per phase. As the lengths are fairly short the unbalance problem is not serious.

Supporting clamps at the upper ends of the ducts were felt to be necessary because of the long vertical runs.

Thermocouples in cages have been drawn about 20 feet into the ducts with the leads for one group feeder and for two generators which are expected to have steady loads. It is uncertain as to whether these couples will read the conductor surface, air, duct-wall temperature, or combinations of these but we should get some interesting comparative temperature data on current, time lag, cyclic loading, effects of changing ambients, etc. The portion of the generator leads retained were not replaced by new cable as it was felt the cost was not justifiable.

The order was divided between General Electric, General Cable, Anaconda, and Okonite to get comparative life data. The conductors are stranded, concentric, or annular depending on the size.

The leads to the potential transformers are 500,000 circular mil which of course are not required for current-carrying capacities but are necessary to prevent overheating on a fault before the breakers have time to open.

Cell Wiring

Kerite and Okonite with 20/64-inch insulation, rubber tape, and fireproof-weatherproof braid were selected for the bus and cell wiring because of its flexibility, resistance to condensation and to water or fog of the fire protective system, and because of the shorter and simpler taps or joints allowable as the material is homogeneous. Shielding could not be used due to the short lengths of cables involved; however, it is unnecessary as the cable is mounted on full-voltage insulators and bushings.

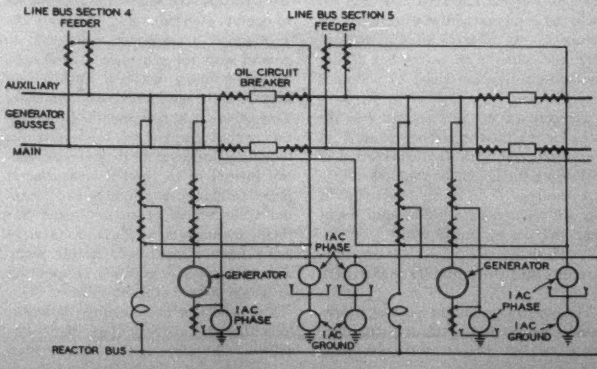
The control cable is the Anhydrex of the Simplex company. Solid conductors were used when possible to eliminate possibility of strands causing short circuits at terminal studs.

Control Conduit

The control circuits are segregated as follows: An individual conduit is run to each circuit breaker. Separate cables are run for the multiconductor breaker control and for the associated current transformers.

There are two control supply feeders.

Figure 7. Generator-bus differential protection



one for the main and one for the auxiliary breakers. Each of these supplies has four stud busses, one for each section.

There are no common pull boxes, terminal rooms, or wire trenches.

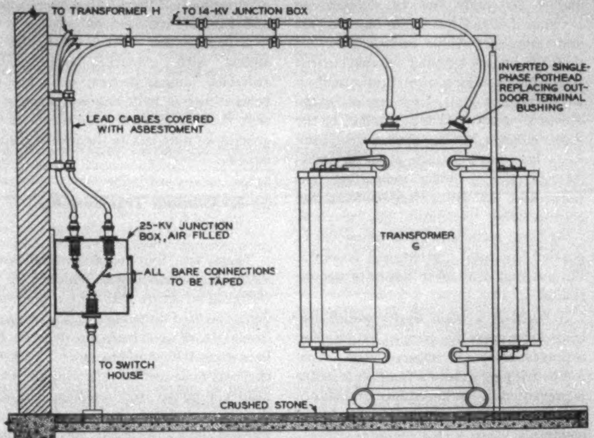

TO TRANSFORMER H
TO 14-KV JUNCTION BOX
INVERTED SINGLE-PHASE POTHEAD REPLACING OUTDOOR TERMINAL BUSHING
LEAD CABLES COVERED WITH ASBESTOMENT
25-KV JUNCTION BOX, AIR FILLED
ALL BARE CONNECTIONS TO BE TAPED
TRANSFORMER G
TO SWITCH HOUSE
CRUSHED STONE

Figure 9. Cable connections from junction box to transformer

Structural Changes in Line-Bus Switch House

Along with the construction of the new switch house there has been a considerable modernization program progressing for the rest of the station.

Cinder-concrete barrier walls have been built between bus sections on all three floors. Bus-sectionalizing disconnecting switches have been installed on both sides of the barrier walls to permit bus sections being tied together in emergencies. This provision should be seldom used since the generator bus sections can be tied together by the reactor-bus or main- and auxiliary-bus tie breakers and as the group feeders between generating and corresponding line-bus sections have separate leads and breakers for the main and auxiliary connections. As the line-bus pairs of sectionalizing disconnecting switches are normally open there is no part of one live bus extending into an adjacent bus compartment which might be contaminated with ionized gases.

Transite and Micarta compartment doors and barrier walls were installed in the line-bus floor to enclose the bus structure and to separate the main and auxiliary busses and their tap connections.

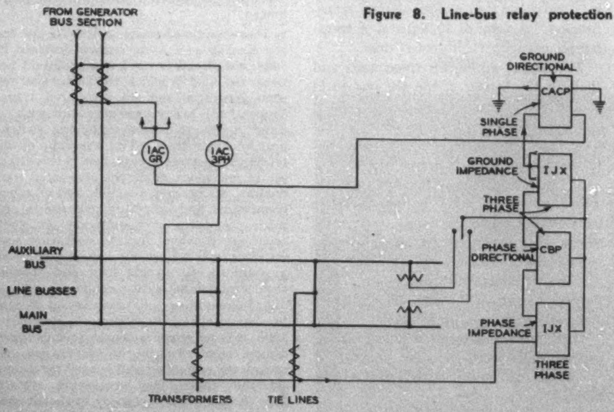

FROM GENERATOR BUS SECTION
IAC GR
IAC 3PH
GROUND DIRECTIONAL
CACP
SINGLE PHASE
GROUND IMPEDANCE
IJX
THREE PHASE
PHASE DIRECTIONAL
CBP
PHASE IMPEDANCE
IJX
THREE PHASE
AUXILIARY BUS
LINE BUSSES
MAIN BUS
TRANSFORMERS
TIE LINES

Figure 8. Line-bus relay protection

The present ventilating system was changed to include an exhaust fan on the roof with manifolds and ducts leading to each bus-section compartment on the three floors.

Modernized Equipment

Many of the line type-*H* circuit breakers were modernized and increased in current-carrying or rupturing capacity by changing contacts, pots, baffles, tie rods, etc. The parts removed were in turn used to increase the capacity of still older breakers especially in the 6,900-volt section of the station.

There were many obsolete and dangerous current transformers and several line reactors replaced by new ones.

The oil-filled bus-potential transformers were replaced by new dry-type transformers connected in wye.

Incoming-line varnished-cambric cables in wall fiber conduits were rerouted or changed to have 25-kv insulation to stop corona cutting at duct entrances.

Overload line relays of obsolete type were replaced by type *CO*. Generator differential relays were replaced by type *CA*.

Five 14-kv switching equipments for station transformers and a motor generator were removed from the 6,900-volt switch house and distributed along the 14-kv line-bus sections.

In order to balance the loads on the four sections and to distribute parallel feeds to substations it was necessary to do considerable interchanging of lines and switching equipments. Certain reactor shifts were required to balance the loads on the parallel lines properly.

Line Bus Relaying (Figure 8)

The usual differential protective system is impractical for the line-bus sections due to the large number of circuits involved. The current transformers are not of a design to hold up their ratios. The sizes are small and there are so many different ratings that the balancing current transformers would be complicated. Ground differential would be impossible as there would be so many secondaries in parallel there would be nothing left to operate a relay.

Reverse-current relays could be installed for each line to differentiate between line and bus faults but the cost and complexity would be excessive.

In the scheme adopted suitable current transformers having special ratio hold-up characteristics and large ratios (type *KC*-51*Y*—1,500/2.5) are installed in the main circuits having appreciable back feeds into the bus such as large transformers, ties to other generating stations, and the group feeders from the corresponding generator bus sections.

As these secondaries are connected in parallel the total current will represent the outgoing load over the lines not included.

A fault on a main feeder would also cause large operating current but tripping is prevented by a directional relay.

Bus tripping due to a fault on a feeder is prevented by an impedance or distance relay differentiating through the feeder reactors.

The various relay elements per double bus section are incorporated into a General Electric type *IJX*12*A*3 phase impedance relay having three instantaneous voltage-restrained current-operated elements each operating on line current and phase-to-phase voltage and one type *CBP*11*A*1 phase directional relay having three directional elements with voltage restraint using line currents and phase voltages, the tripping contacts of these two relays being in series. Similarly a type *IJX*12*A*4 ground impedance relay having three elements as above except using line currents with neutral voltages and one type *CACP*11*A* ground relay using residual line current biased by the current of the generator-neutral current transformers are in series to trip the bus multicontact relay.

As there are 30 to 40 breakers to be tripped per bus section special multicontact relays had to be developed. These 48-circuit relays consisted of a solenoid linked to two drum-type auxiliary switches each having 12 double stages. The relay is star-wheeled and counterbalanced in the open position and requires a positive application of current to cause its operation whereas the other available multicontact relays are spring operated and released by a solenoid. Any slight wear, continued vibration, sudden jar, or inaccurate adjustment might allow the relay to close which would be disastrous to a bus carrying load.

A manually operated multicontact switch is installed between the above relay and the circuit breakers to permit testing of the bus protection system.

As only one bus is normally operated there would not be much advantage in attempting to differentiate between main and auxiliary bus sections.

A four-section control bench was installed with miniature bus, control switches, lamps, meters, etc., for the generating-bus switching equipments except that the control equipments of the generators were left on the former control panels.

25-Kv Outdoor Transformers (Figure 9)

There are four outdoor 25,000-volt 7,500-kva transformers which had an overhead structure with bare copper, and gang-operated disconnects. Cleaning the insulators of soot and fog deposits has been excessively bothersome. This situation was remedied by removing the overhead equipment and replacing the outdoor-type porcelain bushings of the 14-kv and 25-kv terminals of the transformers with single-phase inverted potheads in the same cover openings. Single-conductor paper and lead-covered cables were connected to outdoor junction boxes having removable links for connecting the transformers in pairs. The common connections were then run to the 14-kv and 25-kv switch houses.

Transformer Fire Protection

A permanent fire protective system using Grinnel Mulsifier nozzles was installed for these transformers along with a fifth 25-kv transformer and three 25-kv load- and voltage-regulating transformers. A total of 39,000 kva of transformer capacity is protected thus.

The supply piping for these units and that for the header of the fog system in the switch house is taken to a concrete pit containing the various selector valves. The common manifold can be connected to the city water pressure, to the Boston Fire Department's pumper, or to drain. There is also a line run to two hydrants for portable applicators and to a water screen to protect three large wooden storage water tanks.

Dams were installed around these transformers and crushed stone laid to absorb and cool escaping or burning oil.

Three reinforced metal-lath-and-plaster barrier walls were installed separately, the 25-kv transformers to serve as fire walls.

The two General Electric Pyranol-filled 3,000-kva station-auxiliary power transformers were also equipped with a water protective system which can be used for cooling in case of fire in an adjacent transformer.

Discussion

P. H. Adams (Public Service Electric and Gas Company, Newark, N. J.): The Essex switch house followed the general practice in vogue in 1914 of large switchgear rooms in which the barriers formed by the cell work were the only protection against spread of damage. At that time generating capacity of most systems was small so that short circuits caused relatively little damage. The original plan for Essex was followed generally to the completion of the building in 1923.

In working out the design for the reconstruction described in Mr. Taylor's paper, the principles that we followed are:

1. Improved arrangement of equipment.
2. More definite separation of bus sections.
3. More frequent fire walls and smoke barriers, coupled with ventilation.
4. Limitation of capacity connected directly to each section.
5. Physical isolation of main circuit breakers.
6. Adequate relay protection for the bus sections.
7. Reduction of oil content of circuit breakers.
8. Segregation of control circuits.
9. Better fire-fighting equipment.

It is interesting to note that this question of protection against service interruptions caused by explosion or fire in switchgear houses also confronted the Electricity Commission in Great Britain and at the time the work at the Essex generating station was being started, an investigating board appointed by that commission recommended the adoption of principles very similar to the above for the use of the British engineers.

In particular reference to limitation of capacity in a bus room, they set 60,000 kw as a desirable maximum. This may seem too small for use in the United States, but the principle involved should not be overlooked.

The segregated-phase switch house for the Kearny generating station designed in 1924 and placed in service in 1925 is, I believe, the first in which the switchgear for each generator and its associated transformer bank are in separate rooms with no direct access to rooms containing switchgear for other units. The pole units of the oil circuit breakers on each floor in this house are in one room, while the associated conductors, disconnects, reactors, and all other connections and operating rods are in another. Separate compartments in that room are provided for the operating and interlock rods to prevent any possibility of a grounded rod coming loose and making accidental contact with a conductor.

A failure of a 3,000-ampere oil circuit breaker in one of these rooms in February, 1928, was not communicated to any other compartment even in the same room, although the oil ignited and burned for a considerable time. The ventilating system kept the smoke cleared away so that it was possible to remove the oil from the breaker and extinguish the fire.

It has been our experience that brick or concrete walls are effective fire or arc stops if adequate ground connections are provided for all equipment frames. The ground connections must have sufficient carrying capacity to function under any condition that may arise without fusing. Mr. Taylor points out in his paper that at Essex a complete ground network provides two paths to ground and at least two square inches cross section for all main equipment frames, while for lesser circuits the ground conductor is in most cases as large as the main conductor.

The general principles established at Kearny in 1924 were of considerable assistance to us working out the Essex plans. Improvements in oil-circuit-breaker design enabled us to use the type *H* breaker with its low oil content, thus having less than 300 gallons in the 16 main breakers at Essex, while 27 main breakers at Kearny contain nearly 8,500 gallons.

Essex has a separate room for each main circuit breaker, while Kearny with its unit construction has four single-pole breaker elements in a room.

While the work was progressing at Essex, the entire high-voltage yard at Kearny was rebuilt and differential protection was applied to the high-voltage bus sections, the 13-kv busses and connections, and the main auxiliary power busses.

Plans are now under way for modernizing the equipment at the Marion generating station, where each main circuit will be in a separate room and complete differential protection applied to the busses and connections. This will bring the three main stations of the company up to date as regards main equipment and service protection.

C. R. Reid (Shawinigan Water and Power Company, Montreal, Que., Canada): In reviewing these papers, I have been impressed by the unanimous agreement on the fundamental points under consideration. There were three points which impressed me most:

1. The attempt to improve relay protection and the difficulties with regard to differential features.
2. The necessity of improved circuit breakers and the evident desire to reduce the amount of oil.
3. The stress which has been placed on increased segregation of switching equipment.

In connection with faulty actions of differential relays on through short circuits, two thoughts come to mind. Have any of the authors had experience with the installation of a low-resistance high-reactance iron-core reactor across the coil of the differential relay, to by-pass the direct current? What is the approximate ratio between minimum current settings on the differential bus relays and the maximum through current on fault?

The remarks concerning circuit breakers have proved most interesting. During 1938 the company which I represent purchased, tested, and installed a 6,600-volt 2,000-ampere air-blast circuit breaker. The primary tests seemed to indicate that the circuit breaker in question had a rupturing capacity in excess of 900,000 kva at 12 kv. The opening time from energizing the trip coil to extinction of arc was less than 5 cycles on a 60-cycle base. It would appear that the ultimate rating of this equipment may exceed 1,000,000 kva with a clearing time of less than three cycles.

Considerable interest has been shown recently with regard to air circuit breakers. If this development proves successful, is it possible that the necessity of extensive segregation of switching equipment will be reduced? A consensus of opinion from the authors might prove of special interest.

M. H. Hobbs (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): It seems to me this is a fine series of papers on the important subject of plant modernization, showing that a great deal of study is being given to this reconstruction problem with the aim of improving service reliability and eliminating the possibility of major shutdowns. A few comments seem to be in order.

First, with reference to Messrs. Corney and Edson's paper the statement is made that a decision as to concrete structure versus steel was difficult to make although it was finally decided to use masonry construction. Some advantages of steel were brought out in the paper. In addition to these, steel has the advantage of lighter weight which is particularly important in modernization of existing stations where the floors and supporting walls already exist and may have to be used. The statement is also made that gang-operated switches in metal-clad switchgear are better isolated but that cell type offers better visibility and better segregation. This is not necessarily characteristic of metal enclosure, and complete visibility, as well as segregation of the bus from the switches may be provided in metal-enclosed gear. This is shown in figure 1 of this discussion.

With reference to interlocks, the opinion expressed that interlocks are not required in large stations having highly trained operators seems somewhat at variance with that of other operators. It would seem that in many cases the matter of interlocks is carried to an unnecessarily complicated degree, and that simpler interlocks between isolating switches and breaker, to prevent operating the switches unless the breaker is open, and to prevent access to the breaker compartment unless the switches are open, would be adequate. However, it does seem that such simple interlocks are desirable even in the larger stations.

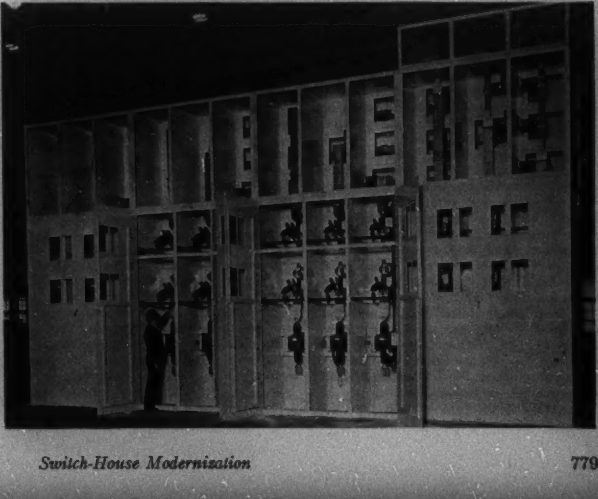
The disconnecting-switch design shown is somewhat unusual and apparently worked out quite well for this particular structure arrangement, where height was an important factor. A number of disconnecting switches have been made, however, using rear-connected studs even when fairly heavy current-carrying capacity was required, in fact, even in "L" Street, disconnecting switches for bus sectionalizing are of this type. However, the problem of expansion must be taken care of as indicated.

With reference to Mr. de Bellis' paper, the outstanding features seem to be bus sectionalization and segregation of the different sections, using metal enclosure throughout, even for breakers and instrument transformers. The operating experience in the case of a fault seems rather impressive.

Mr. Taylor's paper states that cubicles for the reactors were made of concrete so that there would be no undue heating in metal enclosures. It may be noted, however, that a number of installations have been made, using metal enclosures. The arrangement in Essex differs quite materially from that described by Mr. de Bellis, in the fact that metal is not used for the enclosure although every effort is made to carry the ground bus throughout the structure to insure satisfactory operation of protective relays. The statement is made that with the type of indoor breaker used, the forces incident to the closing operation are taken by post insulators rather than bushings. Tests in the high-power laboratory indicate that there is a possibility of fracture of the porcelains under heavy short-circuit current and we make every effort to use material other than porcelain for this application.

In all the papers the importance of the protective scheme, particularly bus differential protection, has been stressed, and the matter is undoubtedly receiving much more

Figure 1



attention than ever before. Metal enclosures are conceded to be of much assistance in providing quick clearing of faults, and limiting troubles which occur to grounds rather than phase-to-phase failures. Even where masonry is used, the effort seems to be made to approach metal enclosure by carrying ground busses to each piece of apparatus and insulator base. The tendency now seems to be definitely away from the segregation of phases by relatively large distances, and group phase construction, with a maximum sectionalization, would appear to be the more favored practice.

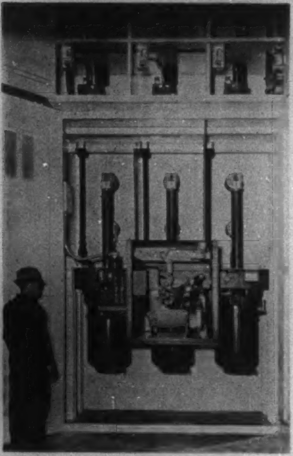


Figure 2

Figure 1 of this discussion shows metal-enclosed switchgear for a section of the main bus before installation in West End generating station of the Cincinnati Gas and Electric Company. This shows quite completely the accessibility of the disconnecting switches and their complete isolation from the bus and circuit breakers which are located at the rear. All disconnecting switches for a particular breaker operate from a single mechanism interlocked with the breaker and the doors to the breaker compartment.

Figure 2 shows a breaker at the rear of the structure, with its mechanism, and the connections to the rear-connected disconnecting switches and bushings. Each phase is metal isolated from the others and potential transformers are located in compartments above the breaker cells, each transformer being in its own compartment and connected to the bus or circuit by means of fuses and disconnecting switches.

A somewhat similar construction has been used in the modernization of the Millers Ford generating station of Dayton Power and Light, except that the busses are located on different floors from the breaker compartments, somewhat similar to the arrangement in the New York stations described by Mr. de Bellis. On the first floor are reactors in metal-enclosed compartments and oil-circuit-breaker cubicles. On the second floor are located the two main busses, together with risers going to the generator breakers on the first floor and feeder breakers on the third floor.

For both the Cincinnati and Dayton installations the fault-bus scheme of protection has been used. Before construction work had been completed a fault occurred in one of the Dayton bus sections which the fault-bus relay cleared successfully. In connection with metal enclosures, a good deal of consideration is being given to this scheme of protection, and where the bus arrangement is not too complicated the protection scheme is very simple. It is believed that further consideration of this method of protection is warranted in the future.

J. W. Lingary (Lynn Gas and Electric Company, Lynn, Mass.): The four papers presented before this committee are indeed indicative of the strenuous efforts and thought that is being vigorously prosecuted to safeguard against traps causing power-system failures which not only interfere with continuous flow of power for the requirements and established routine of the public, but which often result in major loss of property and possibly injury and even death to employees.

It is not my intent to discuss in any detail any one of the presented papers. On the contrary I wish to confine my remarks as a sort of synthesis of personal comment where from personal experience, observation, and study of reports on several major power-system emergencies which have occurred around the country now and then during the past few years, I hope my remarks may be of some benefit. It is needless for me to say that all companies are not cognizant that there exists somewhere on their systems some form of trap which may cause power-system failure of diverse extent. I believe there are. There is no company regardless of size, whose people delegated with responsibility for operation of the power system do not spend their time on oft occasions in worry because they have come to recognize the existence of such traps. By a trap, I mean as some people prefer to call it a "bottle neck." Most companies have them regardless of size and it requires a vigorous, intelligent engineering prosecution to smoke many of them out into the open before trouble and disaster follow.

Most power and manufacturing companies employ highly skilled and competent engineers. In reality most of them are great individual specialists in their respective fields, whose efforts are especially concentrated to the many various components which make up a power system, but in spite of this traps do persist, whether avoidable or unavoidable either in the layout of the company's system or perhaps manufacturer's apparatus. However, when one realizes the vast intricacies that make up a power system, which in general consist of a great many delicate and intricate relays, exposures of transmission and distribution systems to the wrath of natural elements, failure of insulating mediums, the use of high steam pressures and temperatures, and the motion at high speeds of huge bodies of metals, one cannot help but wonder that trouble does not occur more frequently than it does.

We cannot do more than admire the vigorous efforts of engineers today as proved by the papers presented. Their every effort it seems is to prevent, isolate, minimize, and correctly with high-speed dispatch automatically diagnose troubles and expediently clear them by use of correct application of relays and other apparatus. All this must be so, in order to control the follow of an outage either as an unimportant event or at best a very minimum.

In prosecution of these efforts no one should question the wisdom of responsible engineers when they propose justification at times of enormous capital investment. I do not by all means here mean that economy should be forgotten or even slighted. However, I do wish to convey that it should not be overstressed at the sacrifice of system reliability because reliability to some extent is economy of no small importance.

Perhaps there exists nothing short of a dynamite factory where things may happen with such sudden destruction and rapidity as they do on a power system, particularly in the make up of a generating station where there are a great many things which may cause sudden emergencies and even serious outages. It may be only a small control wire or perhaps some small insignificant relay costing a few dollars, which of necessity performs an important function, but at the same time its failure to function properly is capable of shutting down a boiler costing a million dollars. Therefore, we must consider in the design of a power plant a great many small and large complexes. We cannot afford, for example, to load up a boiler house with pipes, boilers, and other apparatus and offer what insignificant space there may be left to install the all and most important station service electrical equipment. The installation of this equipment should have as much effort and thought put forth as to its design, location, and reliability as the major switch house, busses, and switching apparatus. Control wiring should be chosen with great care, and should not be exposed to high temperature, dampness, and other deterrents. Important control terminal centers, delicate relays, and equipment of this sort should be housed in the cleanest and most desirable places that can possibly be found. I believe that no important major station cables should be of the lead-covered type with their incident potheads and vulnerability to break down. In general, I believe these cables should be mounted in suitable raceways, insulated and mounted on insulators designed for operation at least at full voltage. Important station transformers should be segregated as much as possible away from buildings and one another and protected with suitable rapid fire-fighting equipment. Transformer-oil drain valves should be remotely controlled so that in event of fire, oil may be withdrawn quickly if necessary. Station ventilating systems should have a reliable source of power consisting of main and auxiliary, because in event of explosion, if the use of ventilating fans is lost a considerable length of time elapses before men are able to enter and work. I cannot speak too highly of the efforts made in connection with providing suitable fire-fighting equipment. It has been my experience that the use of

CO_2 automatically controlled is most desirable. I have known of cases following a major explosion where CO_2 was immediately injected and there was little or no evidence of deposit of smoke or volatilized metals throughout the switch house. I believe the smoke and gases were so rapidly and thoroughly cooled and emulsified with CO_2 which I believe prevented their spread and concentrated deposits. Based on this experience, I would recommend highly automatic CO_2 installations for all segregated switch rooms and other similar important locations particularly if inflammable materials are present. Every effort should also be made to design bus and switching compartments against the entrance of rodents. Many a bad spillover has been experienced from this one cause alone. The interior of switch rooms must never be painted except with proved fireproof paint. I have known of a very bad shutdown from this cause where the wall paint caught fire following a serious explosion and continued to burn for some time. Skylights over turbogenerators, switchboards, and other important station equipment are extremely bad in event of severe storms. Similarly no important station equipment should be installed in basements or various pits where it is subject to inundation from flood waters or even from bursting or badly leaking water mains. Coal storage, handling, and conveyor systems including docks especially should be protected against fires and coal-dust explosions. Oil storage systems whether for lubricating or insulating purposes should be held to a minimum indoors and especially protected against fires. Oil piping should not be in close proximity to hot steam pipes; if so they should be adequately protected against fire as result of oil leaks. Standardization and maintenance of adequate and essential spare parts are absolutely necessary in any power plant.

We must not in our efforts when considering the physical arrangements of a power plant forget for one moment its personnel, whether it be a switchboard operator in the control room or an operator at the turbine throttle, or an operator in the fire aisle of the boiler house, because they are exceedingly important persons, probably not often recognized as such. In general they must and should be highly intelligent and skilled individuals. I have known it to happen where due to some form of mental lapse or for some psychological reasons they may become individually the biggest and most dangerous trap of the power system, because during an emergency they may emotionally or otherwise fail to carry through the proper operating function. Great care must therefore be used in the choice and caliber of these men for their respective positions. They must be properly instructed, they must never be instilled with a feeling of inferior complex by supervisors or others, they must not be overstressed that severe punishment will follow their mistakes. Every effort should be made to ascertain that these men have no detrimental habits, home or financial worries which may deter or otherwise interfere in the correct and vigilant execution of their duties.

We must remember that perhaps two emergencies are probably never exactly alike. There may be long intervals between emergencies; howsoever the case may be, operators must and are expected to be alert to carry the responsibility of their function. Therefore, it seems reasonable that frequent drills and instructions are absolutely necessary, mimicking all possible emergencies which might probably occur.

In closing I might say we learn a great deal from the other fellow's sad experience. We may well copy the highly efficient efforts of insurance companies who in general investigate and study every accident of their clients, whether it be to an employee or property. They then correctly classify it and make every strenuous effort to eliminate all such possibilities of repetition throughout their clientele. Therefore, I believe it is quite in order that we should have a committee of specialized engineers who would investigate and study and report in classified detail all happenings incident to major power system difficulties for the benefit of all of us. We then may be able to proceed more intelligently in scrutinizing our own power system for near like or similar pit falls.

A. P. Fugill (The Detroit Edison Company, Detroit, Mich.): I would like to discuss particularly the two papers presented by A. M. de Bellis and D. W. Taylor.

These papers indicate rather definitely certain major trends in design for stations where large amounts of energy are concentrated. Briefly these trends are: automatic bus protection with resultant electrical sectionalization; elimination of oil-filled apparatus, or at least reduction in the amount of oil used; and localization of trouble by physical segregation of equipment and adequate fire-fighting equipment. It is not necessary to cover these factors in detail as they already have been discussed adequately by others.

It is rather evident that there is general agreement among switch-house designers on these general principles but considerable difference of opinion exists as to the extent to which these principles should be applied in any modernization program and how the desired results can best be accomplished. Although the question of economics is present, it is modified by the indefinite factors of the probability of the occurrence of trouble and the effect of a serious disturbance on public good will. It is usually proper to spend considerably more money than could be justified by equipment damage or direct loss of revenue, because of the possible effects of such a service interruption on the company's relations with its customers. Because of the indefiniteness of this factor, there is a tendency, especially on the part of those who have experienced such a major disturbance, to adopt designs which are rather expensive, so as to obtain an extra factor of safety. Since there is no positive criterion, the judgment of the designer and his associates must be relied upon to strike the right balance.

Although several features of station design described in Mr. de Bellis' paper merit comment, I will confine myself to a short discussion of the bus and bus housing. Without doubt, the design used is unique and, as was pointed out in the paper, has several advantages over the more conventional self-supporting, rectangular metal housing with metal baffles between phases and with the bus mounted on one or, at most, two insulators. The installation is undoubtedly easier because of the smaller pieces to be handled but it appears that the over-all cost of the bus and housing would be higher. In the design described in the paper, there are the heavy supporting rings which should be of nonmagnetic material and the four insulators per support with the proper provision for initial adjustment and movement of the bus due to expansion. The enclosing covers are made of expensive, nonmagnetic materials, and the structure for supporting the three assemblies, though of structural steel, is quite heavy. It would be interesting to know whether Mr. de Bellis has any cost comparisons on the different types of bus and housing.

The use of four insulators for each point of support gives an exceedingly strong bus for forces in all four directions. In determining the required mechanical strength of a bus, the only force which is important is that due to the electromagnetic effect of the fault current. This force will be in the direction of a line through the three busses and not at right angles, except for a minor effect where the bus changes direction. Two of the insulators used in this design, therefore, are of little use. There may be some justification for two insulators so that one insulator will always be in compression. However, we have carefully designed all our heavy duty busses in recent years to insure mechanical sufficiency and have not found a single case where more than one insulator was necessary, with spans of four or five feet and initial symmetrical root-mean-square currents up to 50,000 amperes, even though, in some cases, the insulators were stressed in cantilever.

There is a good reason for keeping the number of insulators to a minimum since the insulator is generally the weak point in the installation electrically. With proper clearances, a flashover to ground usually occurs over an insulator because the distance to ground is less at this point, the surface of the insulator may become dirty, or the porcelain may break. We believe that the fewer insulators in a bus run, the less the chance of trouble, assuming, of course, sufficient mechanical strength.

Mr. de Bellis states that the bus is insulated for 23 kv throughout its length which we assume means through the insulator heads as well, or the benefit would be largely nullified. The purpose in insulating a bus is to reduce the chance of flashover in case conducting gases should leak into the housing. We have felt that with a reasonably tight metal housing, there is little chance for conducting gases to enter the enclosure in sufficient quantities to cause flashover even with a bare bus. The use of insulating material, on the other hand, in case trouble does occur, introduces the additional hazard of smoke and even explosive gases from the combustion of the insulating materials. We wonder what Mr. de Bellis thinks of the possibility of sufficient internal pressure being developed to blow off the housing covers with consequent hazard to personnel and damage to equipment.

In his paper on modernizing switching facilities for Essex switching station, Mr. Taylor states that masonry enclosures for equipment were used, perhaps because some of the present cells and bus housings could be utilized. I would like to ask Mr. Taylor whether he feels that such construction would be adopted for a new station of similar character, or whether he would then use metal enclosures with building walls to provide fire barriers.

Mr. Taylor mentions the ground network in the station and states that equipment is grounded to this network. Does that mean that each insulator base is thus grounded? Are there any reinforcing rods in the masonry housings and, if so are they grounded or is there some provision for keeping ground current out of these rods? Is the ground network tied to building steel or building reinforcing rods in any way? The answers to these questions have a vital bearing on the very important problem of the potential hazard resulting from undirected fault currents flowing in a switching station or power plant. Recent experiences have indicated that considerable damage can result from ground fault currents flowing in control conduits, reinforcing rods, and other paths of reasonably low impedance but limited cross section. Wherever equipment housings are in contact with the building structure, the possibility exists that fault current will flow in the wrong places to reach the ultimate ground mass. However, the danger of trouble is reduced to a minimum if a low impedance path of adequate current-carrying capacity is furnished to the ground mass from every point to which a flashover can occur. One of the advantages of metal housings over masonry housings is that a flashover must occur to the housing before it can reach any part of the building. It is then comparatively easy adequately to ground the metal housing. In a masonry bus structure, especially if the insulator bases are not grounded, fault current may get into the reinforcing rods and thence into the building where control conduit and reinforcing rods are usually buried. Adequate grounding of such a bus structure is difficult to accomplish. In designing the ground connections, it should be remembered that reactance is just as important as resistance in obtaining low impedance, so that merely furnishing a large cross section of copper is not sufficient. Proper location of grounding conductors and parallel paths for the ground current are necessary to minimize the reactance of the path to ground. We have felt that the steel framework of the usual station furnishes a very good ground network, and, in general, connect our copper grid ground network to the building steel at frequent intervals.

E. S. Fields (The Cincinnati Gas and Electric Company, Cincinnati, Ohio): In the modernization of the switch houses covered by this group of papers, considerable emphasis has been placed on the isolation of bus sections by gas-tight barrier walls, and in most every case there has been included a comprehensive ventilating system to facilitate clearing of smoke and fumes in the event of fire. Such ventilating systems are usually of high capacity and in order to get them to function promptly in the event of fire some of the systems have been made to start automatically.

It has been our observation that most of the severe switch-house and substation fires have had considerable pressure associated with them and that the results of the fire have been most severe in cases where the equipment involved was confined in a small space. Based on this observation, it has been our most recent practice in Cincinnati to isolate groups of switching and other equipment by barrier walls and install ventilating systems much in the same fashion as described in this group of papers. At the same time, however, we attempt to have oil-filled equipment facing at least one outside building wall with loose panels or hinged doors or windows in the wall that will blow open to the outside in the event of extra pressure caused by fire or explosion. It is believed that this means of relieving the pressure to prevent spread of smoke, fire, and gases is an effective one and worth consideration in new design and in modernization programs where it is practical to apply it.

R. L. Frisby (Kansas City Power and Light Company, Kansas City, Mo.): The four papers presented on the subject of reconstruction and modernization of switch houses and switching equipment have covered about every phase of the problem in an excellent manner. The subject is of interest to all operating men and operating companies, more especially to those concerned with operating systems that were built about 20 years ago.

The activity at this particular time on reconstructing and modernizing was undoubtedly brought about not only by the expansion of these systems, but due to the fact that several very serious outages and complete or partial shutdowns of systems have occurred in the past three or four years. To prevent a reoccurrence of similar accidents it is very evident from the papers presented that a great deal of time, study, and money have been spent in modernizing the several systems described.

There is, however, another side to the question which may be given some consideration. We are well aware of the fact that a vast improvement has been made in oil circuit breakers, and from records and data collected I am informed that no oil fires have resulted in the past two years caused by the failure of any modern breaker or modernized breaker installed within the past five years. If this is true, can we justify the expenditure necessary completely to rebuild or reconstruct our bus structures and switch houses in order that fireproof walls may be built to segregate groups of busses and switching equipment? True, our old bus structures may not lend themselves as we should like and desire to the installation of additional current transformers necessary for the relaying and segregation of bus sections or groups; however, several relaying schemes are available and I believe it is possible for the engineer to use some one of these schemes on his existing structures and system, provided he can make up his mind which of these relaying schemes will best fit his layout and give the protection desired, without adding too great a hazard due to faults in the operation of the relaying set-up.

Granting that it is possible to modernize our circuit breakers and install a relaying scheme which will give us reasonable protection and segregation of busses, then if we go through our switch houses with a fine-tooth comb and correct the weak spots, mechanically as well as electrically, install fire-fighting equipment, and last but not least, not overlook the house auxiliary system, which may be an equally or an even greater hazard than the main bus layouts, so far as causing prolonged outages are concerned, are we not justified in taking some gamble on an outage which may or may not occur once in 20 years?

Carl M. Gilt (Consolidated Edison Company of New York, Inc., New York, N. Y.): One of the outstanding trends in the modernizing of the older switch galleries as well as the construction of new galleries is the more extensive use of sectionalization and segregation, both electrical and physical. The necessity for reducing the magnitudes of short circuits, because of limitations in circuit breaker interrupting capacities, the difficulty in withstanding the magnetic forces and thermal destruction of enormous currents, has been only one factor in this trend. Were this the only factor, the results could be secured by a judicious use of reactors and breakers without physical separation.

However, experience with failures on station busses of large capacity and voltages of 11,000 and higher demonstrates that a failure may not be confined to its point of origin, even with fast-operating breakers. In the older stations of smaller capacity and particularly with voltages of 6,600 or less, arcs frequently went out with the drop in voltage even though no automatic protection was provided for the busses or generators, and the damage was more or less local. A failure on a large-capacity bus is so explosive in nature and the ionized gases spread with such rapidity that ordinary breaker compartments and doors and bus compartments offer no guarantee against a cascading of failures. Smoke from burning insulation such as tape or oil, will rapidly deposit soot on insulators, frequently with resulting flashovers.

The trend, therefore, has been to separate physically one bus section from another to prevent the spread of damage. Bus sections must be relatively small so that two adjacent busses may be lost simultaneously without too seriously crippling the supply to the load, for the bus failure may very well involve or originate in a bus tie breaker. Double breakers, or a section of bus normally dead with adequate fire walls, are very instrumental in reducing the likelihood of a failure involving adjacent sections. Fire walls between important sections should be complete without being weakened by a door that might be blown off its hinges. Double doors are an improvement, but still better are solid walls with no direct passage between sections, openings being through fire doors into a corridor or intermediate room.

Ventilation must be adequate and sectionalized to insure that smoke can be rapidly scavanged and will not spread from one section to another. Also the sectionalizing of control and conduits must be carefully followed as a high-voltage failure readily may result in destructive currents and potentials on control conduits and cables. Adequate drainage of high capacity must be provided to prevent the spread of such currents and nullify the whole protective system.

Perhaps most important of all is the keeping of a watchful eye for what may appear to be some unimportant detail that may jeopardize a fine one-line diagram or fundamental floor plan. Pieces of cable which look like a feeder but are really part of a bus have a queer way of getting into the wrong room. Bus sections well separated by breakers, disconnects, and barriers on one side of a wall may have only a thin piece of asbestos lumber between them on the other side of the wall. Control conduits may be well separated and protected for their whole run and then come together in a pull box with only a thin sheet metal between them and some circuit breaker. Some ventilating duct may be air-tight as long as it is there but when it melts down a fine chimney is provided from one section to another. Such things occur in building a new station. They are more apt to happen in modernizing an old station where existing space limitations result in odd contortions, but how frequently they sneak into an old station when one is trying to put 100,000 kw where 25,000 kw belong and three extra feeders must be got out of a station already full. And, of course, with one eye always on the dollar sign, we find that the other eye, perhaps too conveniently, does not always see all that it should.

H. H. Rudd (Railway and Industrial Engineering Company, Greensburg, Pa.): My remarks apply to that part of Mr. de Bellis' paper which relates to the bus and disconnecting switches.

When my company as manufacturers knew that the Consolidated Edison Company wanted to modernize and install equipment of a very rugged character, we had no preconceived notions of how big or how strong such equipment should be or how it should be designed. The specifications given us were rigid—far more so than any we had ever encountered. Among the requirements were:

1. A low temperature rise for bus and switches.
2. The bus to be insulated with wrapped varnish cambric insulation and, in addition, to have insulators in compression holding the bus at four points.
3. The strength of the supports to be 10,000 pounds in any direction at right angles to the center line of the conductors.
4. Each phase conductor to be enclosed in its own walled metal housing with air space between the housings isolating one phase from the other.
5. The housings to be tight to prevent dirt and powdered coal dust from getting in on the porcelain and insulated conductors, so as to reduce the outage time for inspection and cleaning.
6. Baffles to be placed in the bus runs to seal off between the bus and housing in much the same way as fire walls are used in the building to seal off one part of the station from another.
7. A ground bus to be run so that every bus frame and sheet of housing be substantially grounded.
8. Switch clips and blades to be held in a similar way to that of the bus by four insulators in compression.

Our designs in general followed these requirements as set by the Consolidated Edison Company to meet their particular conditions. In making design studies we found that the form of bus and housing tended toward some specific patterns, which might be interesting.

1. Because of the rigid requirements for wrapped insulation, the form of conductor chosen was a round tube. The splices, expansion joints, ells, tees, and crosses were all of a circular cross section for ease in applying the varnished cambric insulation.
2. The bus support frame was made in the form of a ring. This gave a construction of maximum stability to support the insulators and obtain the required strength, no matter in which direction the stress might be. This round frame also permitted a machining to give a smooth surface against which the housing plates are bolted and also a machined groove in which gaskets are placed to make the joint tight. The frames are cast bronze.
3. Mounting feet cast integral with these rings provide the means for fastening to wall, ceiling, or supporting framework. Any short-circuit stresses are carried directly to the supporting members and are not carried through any part of the housing sheets.
4. The housing in two semicylindrical halves is clamped down bridging the space between two adjacent frames and thus forming the enclosure. Gaskets are provided to seal the space between the two halves of the housing. There are no louvers in the frame or housing. The rounded form of the housing makes a very effective surface in getting rid of the losses by convection as it is streamlined compared to a flat rectangular construction. The rounded form also minimizes the sheath or housing losses.
5. For straight bus runs the housing is made of manganese steel which is nonmagnetic. For the ells, tees, etc., where it is necessary to cut the sheets in specific forms for welding into the special shapes required, the manganese steel is too hard and, therefore, a silicon bronze such as Olympic bronze or Everdur is used which can be cut easily and welded to the desired form.
6. The simple units of structure, bus support frames, conductor, and housing permit an easy method of erection and quick assembly at low cost.

In the preceding remarks I have attempted briefly to show the nature of the design which was used to meet the rigid requirements of the Consolidated Edison Company. For equal requirements it is less expensive as judged by previously accepted standards which do not incorporate the features that the Consolidated Edison Company now has. I think it is only fair to state that the Consolidated Edison Company's needs and experience since the first installation seem to justify such rugged construction and such high factors of safety.

We have, I am glad to state, found that where requirements are less severe, a similar construction can be made which, though not so rugged, embodies a number of the advantages of the Edison construction.

With less severe short-circuit stresses, lighter frames and lighter insulators can be used. If the requirement against dirt is not severe, then it is possible to omit gasketing and the machining for gasketing and still provide a tightness comparable with conventional concrete cell and door work, or comparable with flat overlapping sheet work. The plates are thinner but they still act as an effective housing.

If there are no requirements for covering the bus with an insulating material, then open forms of conductors can be used such as flat bar bus, or channel and angles, or ventilated square tubing, and advantage taken of the better ventilation of the conductor and more simple methods of making splices, etc.

The Consolidated Edison Company uses a ground bus. The same form of supports and housing can be used for a system using a fault bus. Insulation readily can be placed under the feet of the bus support frames.

The general form of construction supplied to the Consolidated Edison Company is flexible enough in design to give the ruggedness and factors of safety that it required and, at the same time, it has features that can be incorporated to advantage in bus work where less severe conditions are encountered.

F. W. Gay (Public Service Electric and Gas Company, Newark, N. J.): The method of bus construction described by Mr. de Bellis has been worked out with great care and we believe should find a place of extensive usefulness in switch-house design. While metal bus structures have certain desirable features, the insulating advantages of a properly constructed concrete bus should not be overlooked. The insulating value of concrete in bus and cell structure has been known for a generation. A recent failure at Essex generating station on a new bus led to the making of tests to determine the value of concrete as an insulator in such structures when new and when seasoned. It is believed that all the material available on the insulating value of concrete could well be collected and presented to the Institute in a paper.

Two feeder busses at Essex generating station which had been installed for over ten years were scheduled to be demolished. The doors were taken off, leaving the cell structure open, and windows were left open for several days during drizzling weather to allow moist air to blow through the busses. These bus structures were made of well-washed sand and gravel and fresh cement. Each bus support comprised a porcelain insulator, bronze top, and malleable iron base bolted to a cast iron insert cast in a concrete slab, in turn built into the masonry bus structure.

The busses were excited to 8,000 volts through a transformer connected to the 440-volt auxiliary power bus, and the 440-volt breaker was set to trip at 1,000 amperes. One end of a flexible cable was attached to the insert and the bus support insulator was short-circuited by touching the other end to the hot bus.

After a number of supports were tested, it was found that the arc was very feeble (not over one-half inch long) where the bus support insert had an insulation to ground in excess of 200,000 ohms and thereafter all tests were confined to the lower-resistance inserts. The maximum length of arc on any insert at 8,000 volts was three-quarters of an inch and there was no evidence of any increase in length when it was held on for approximately 15 minutes.

It was decided to test the lowest-resistance insert to destruction at 15,000 volts instead of 8,000, as obviously very little advantage would be obtained by using normal voltage, and much time would be wasted. The insert tested was in the bottom row, mounted in a slab cast directly on the floor. After the voltage had been on for approximately five minutes, the arc which had started with a purple streak approximately one inch long had lengthened to $1^1/_2$ inches. At the end of $8^1/_2$ minutes the arc had lengthened making it possible to draw it down across the insulator so that it held across the porcelain to the base, and from then on it was allowed to play across the insulator. At the end of $10^1/_2$ minutes, the current was sufficient to trip the circuit breaker and it was found that the concrete around the cast-iron insert was smoking hot and had cracked and was slightly spalled. After the slab was removed from the floor, the floor was not in any way damaged.

Tests to determine the distribution of voltage around the cast-iron insert showed that the major part of the voltage drop between insert and ground was confined to a region of not more than one inch from the insert.

It is proposed to remodel the Marion generating station in the near future and the insulation resistance through the masonry structure to ground has been taken for the concrete inserts under the bases of every bus support in the bus structures of this station. Ninety-seven-and-one-half per cent of these inserts showed an insulation resistance to the station ground grid in excess of 100,000 ohms and 75 per cent in excess of 1,000,000 ohms. The lowest resistance measured was 20,000 ohms and the highest 20,000,000 ohms.

H. L. Wallau (Cleveland Electric Illuminating Company, Cleveland, Ohio): Modernization of electrical switch houses is an effort to improve reliability at a minimum of cost, using existing buildings and equipment unchanged to a maximum degree compatible with the end in view. Such changes as are made generally involve reductions in maintenance costs as well.

Because of the limitations which confront the designer under these conditions, limitations much more onerous than those met with when designing absolutely new facilities, the problems encountered are much more difficult of solution.

In general the following criteria must be realized to the greatest degree possible:

1. A type of construction which will minimize the possibility of faults developing which are internal to the structures.
2. Fast relaying to initiate the clearing of such faults as may occur, in minimum time.
3. Limiting the fault currents which will pass through the breakers to values within their interrupting abilities.
4. Physical isolation of equipment individually or in groups to confine such damage as may occur to restricted areas.
5. Electrical isolation to prevent a fault in one section from involving another section through damage to a single sectionalizing device.
6. Suitable means of ventilation, preferably automatic, to clear any area in trouble of fumes and gases in minimum time, to allow quick safe access to the area.
7. Suitable means of trapping or disposing of oil which may issue from damaged apparatus coupled with means of fighting the electrical fires which may occur.

In addition there should be,

8. Proper correlation of the supply capacity to the load capacity of each section, preferably so that the loss of one of several sources of supply when provided to a given section will not curtail its output.
9. Proper correlation of loads connected to the various bus sections so as not to cause a partial loss of system load in the event a bus section is lost.

How well these criteria have been met in the modernization plans for the four stations under discussion is obvious. The design engineers are to be congratulated on the manner in which they attacked the problems, and on the unique metal-clad bus construction which they developed.

H. R. Summerhayes (General Electric Company, Schenectady, N. Y.): All of the modernizing layouts presented in the papers recognize the importance of physical and electrical segregation of bus sections, normal ventilation and special ventilation for scavenging the products of combustion, means for preventing the passage of incandescent gases from one section to another, and modern fire-fighting equipment.

In some of those installations it appears to me that ground-fault protection for the bus sections might have been used to advantage.

Tradition and custom have had a certain influence on the station designers preference for the older and better established differential protection; nevertheless, in the ten years or so since the ground-fault protection scheme was introduced, it has been adopted to a considerable extent, as shown by the report on "Bus Protection" by the relay subcommittee of the AIEE protective devices committee (AIEE TRANSACTIONS, volume 58, 1939, pages 206–11, May section).

This committee gives 197 installations of the fault-bus protection reported by 11 companies as against 803 installations of the full differential protection, or nearly 20 per cent of the total. Also reported are 132 partial differential relay schemes using distance relays, etc.

The difficulties and complications encountered in applying full differential protection are described in a paper by R. M. Smith, W. K. Sonnemann, and G. B. Dodds (AIEE TRANSACTIONS, volume 58, 1939, pages 243–9, June section).

In new structures where metal enclosure for the bus bars and switchgear can be used the installation of ground-fault bus protection is comparatively easy, and would appear to be cheaper and far simpler than the full differential protection.

In new structures utilizing concrete or masonry enclosures the designer can draw on past experience for the precautions necessary to prevent diversion of the ground current from the fault bus at other paths in the structure. These precautions should be taken anyway whether ground fault or differential protection is used, as admitted in the Corney-Edson paper. Also in either case there must be furnished a substantial ground bus of low impedance and adequate current-carrying capacity, to which are connected the bases of the bus insulators, circuit breakers, disconnects, and other points to be grounded.

Therefore, the expense of these measures should not be charged against the fault-bus protection, in comparing it with differential, and taking this into consideration the fault bus, with only one current transformer per bus section appears simpler and cheaper than the full differential scheme, and offers advantages in saving of space and elimination of many secondary connections.

The ground-fault protection practically eliminates phase-to-phase faults, especially where fast switching and relaying are used, since a phase-to-phase fault cannot take place without involving ground.

Ground-fault protection is also well adapted to outdoor switchgear installations, as proved by the experience of a number of companies using it.

The severity of faults, the amount of destruction, spread of metal vapors, etc., should be reduced by the ground-fault scheme, since the current in the fault is limited by the neutral grounding resistor.

Incidentally, the severity of bus faults in new layouts, whether differential or ground-fault protection be used, should be reduced by the high operating speed of the circuit breakers and relays used in modern switchgear.

Neutral grounding plans must be studied carefully as to the adequacy of all equipment in the neutral both as to insulation and current-carrying capacity. The reduction of the amount or elimination of oil in circuit breakers should not give a sense of false security, since there may still be oil in other equipment, and there will usually be other combustible insulation, so that fire extinguishing and ventilation will still be necessary.

John G. Noest (Brooklyn Edison Company, Inc., Brooklyn, N. Y.): In two of the four papers presented, and in their subsequent discussion, it was admitted that difficulties were encountered in the economic justification of the expenditures involved in the modernization programs. In these cases engineering considerations prompted the outlay of capital for improvement in reliability, improvement in expected continuity of service, and to minimize damage to equipment in case of severe disturbances. In short, these expenditures were made to prevent plant shutdown, or to keep a service interruption which might occur, to a minimum of time.

There are in general three divisions into which plant shutdowns may be classed. First: failure of equipment due to insufficient capacity; second: failure of equipment to perform as designed; and third: improper operation of equipment.

The first and third classes are a matter of design. The first class includes all cases, where due to increase of capacity on a system, or due to installation of system ties the short-circuit duty on breakers and busses exceeds their interrupting or carrying-capacity respectively. This condition, as well as the segregation of equipment to limit damage, is a function of design and the modernizations carried out are remedial measures for it.

The third class is also a matter of design. Improper operations of equipment occur not as the result of intention, but as the results of error. The probability of errors made by operating personnnel is not a function of the salary classification nor of the length of service of an operator. Improper operations just happen. However, means are available to the plant designer, in the forms of interlocking systems, to enforce proper operating procedure in most cases. If extensive modernization of equipment can be justified it seems that the comparatively small additional cost of interlocking devices should be easier to justify.

It is perhaps the second class to which most of the past plant shutdowns may be charged. Failure of equipment to operate as designed is a function of maintenance. As an example: a circuit breaker, designed for an interrupting capacity of 1,000,000 kva may be incapable of interrupting 100,000 kva if its opening stroke has been slowed down by excessive friction due to corrosion or lack of lubrication. The circuit breaker may not open at all on account of a small cotter pin being sheared off, on account of a small bolt broken off, or on account of a little rust in a strategic place. The most inclusive differential relay protective scheme may be put out of commission, unknown to anyone, by a short circuit in the current transformer, or its secondary wiring. Such conditions may never be discovered and will not be found out in a post-mortem after the fire department is through with the plant. When an insulator flashes over, something has happened to its insulating strength before it flashed over. After a flashover the evidence is usually destroyed. If only a small percentage of the thinking done by the engineers responsible for design of equipment or the engineers responsible for the plant layout was spent in preventive maintenance the history of power-plant failures would surely lack many a page.

It seems that along with the modernization of equipment, modernization of maintenance methods are in order. And not only is modernization of maintenance methods in order but the establishment of closer ties along which experience and information may flow from the maintenance organization through the engineering organization to the manufacturer and back. Modernization of maintenance procedure is not an alternative to modernization of equipment but a corequisite. Its cost is generally small.

H. A. P. Langstaff (West Penn Power Company, Pittsburgh, Pa.): The program of modernization described by A. M. de Bellis of the Consolidated Edison Company of New York is so thorough, complete, and general in its scope as to make it difficult to formulate specific comments. We have witnessed the manufacture and assembly of the metal-enclosed bus equipment, such as is being used at Waterside Number 2 station as pictured in figures 6 and 7. It is so strongly constructed mechanically, electrically and thermally that it is difficult to see how there can be any service failure resulting from it or from any external influence other than complete structural wreck. We have also seen during manufacture and assembly a sort of junior class of this metal-enclosed bus equipment, wherein by using aluminum enclosures the weight is considerably reduced with bus insulation values retained at the same high level. The enclosure is not mechanically as strong as that which Mr. de Bellis describes, but it appears fully satisfactory for general application. Tribute should be paid to the engineers of the Consolidated Edison Company for their courage and ability in developing this outstanding new type of power station bus.

In the paragraph giving the seventh step of those considered most important effectively to confine damages for equipment failures, Mr. de Bellis makes reference to the power supply system for station auxiliaries and for generator excitation. I wish to emphasize that this step should be given equal weight with other steps in attaining the results desired and that it should not be regarded as an auxiliary or secondary step. Careful analysis should be given and rigid inspection made of the station auxiliary systems lest a bottleneck occur which might obviate the apparent foolproof construction of a major power station facility. Emergency transfer equipment may be provided in many places and if so care should be taken that the transfer equipment itself does not bring to a vulnerable focal point the two supply sources. A failure in the transfer equipment can very well cause both power sources to become inoperative. The same care should be given to the minor electrical system as is given to the major electrical system.

Proper segregation must be carefully maintained of control supplies and circuits to adjacent sections of main power busses. Interconnection of current transformers located on different sections of the main bus should be made with due care that faults occurring on one section of bus cannot be carried to another through the secondary wires of the interconnected current transformers. Vigilance must be exercised to ascertain where bottlenecks are located and to prevent them from developing through hurry or falsely economical engineering practices.

T. W. Trice (Consolidated Gas Electric Light and Power Company of Baltimore, Md.): At a time when switch-house modernization is receiving particular attention, the paper by H. E. Strang and W. M. Hanna summarizing the means which have been used, or are available to carry out a modernization program is of special interest. There are, however, certain items that logically might be included along with those covered by the authors.

The problem of isolation of bus sections and equipment usually results in the construction of compartments to contain this equipment. Where this type of construction is required, which is usually the case with rebuilt switch houses, some attention should be given to the pressures that may be built up in the event of an explosion. Our experience with switch-house explosions back in 1927, where confinement was not particularly great, revealed that considerable pressures can be built up with rather severe effects, and we believe should be given due recognition in any switch-house design.

Where compartments are used care should be taken to see that an operator cannot be trapped if a failure takes place while he is in the compartment. A means of mitigating this would be to have exit openings at either end of the compartment, one of which may be used only as an emergency exit.

Where isolation of sections and equipment is produced by compartment walls some form of forced ventilation frequently is required to scavenge smoke and gases out of the compartment subsequent to a failure in that compartment. This ventilation equipment should be of sufficient capacity to rapidly dilute smoke or gas but, most important, it should not be destroyed by the original failure and the source of power should be such as to be independent of any switch-house failures, thereby assuring its readiness for service when needed.

The question of fire protection should also be given attention in any switch-house modernization program. This attention should be directed not only toward having the necessary fire-fighting equipment available, but assure that it is possible to combat any fire without danger from toxic gases or live electrical equipment. In this connection it appears that water in the form of a spray has the greatest all-around possibilities and if we could look into the future we might see the weatherproof type of equipment used on indoor installations with water-spraying facilities permanently installed.

In the fore part of the paper, several factors were listed as being included in reliability of operation. It would appear that this list might be extended to include "ability to restore service in the event of an interruption."

There are included six causes, any one or more of which may be the basis of a modernization program. It does not appear that reliability of service is given sufficient weight, for in the final analysis the primary object of any modernization is to improve reliability of service. This improvement may be secured by carrying out one or more of the items listed, these methods being only a means to an end.

The use of photoelectric tubes has been mentioned as having possibilities for bus protection. In addition to lack of experience another disadvantage of this type of protection is that it presupposes the existence of an arc. Incorrect switching of ground disconnects or failure to remove grounding devices may result in a solid ground fault. To insure against this the photoelectric-tube installation would have to be backed up with another type of bus protection which could just as well be designed to handle the trouble initially.

D. H. Johnston, Jr., and E. F. Wolf (Consolidated Gas Electric Light and Power Company of Baltimore, Md.): The paper by D. W. Taylor presents a rather complete résumé of reconstruction details, which should be of real interest to the many concerned with the modernization of generating-station and switching facilities. Reference to a permanently piped-foam system on four 3,750-kva station-auxiliary power transformers at Essex prompts a note of warning on the use of such systems.

Tests were recently conducted by the Consolidated Gas Electric Light and Power Company of Baltimore to ascertain the relative effectiveness of fire-extinguishing equipment for transformers. The results of these tests conclusively demonstrate that the use of piped-foam and piped-carbon-dioxide systems, unless properly applied, increases rather than reduces the fire intensity. It is essential that the injection of foam or gas shall produce no agitation of the oil either by velocity contact or by deflection from projecting steel bracing in the tank or under the cover. In several of the tests the introduction of these extinguishing agents converted a comparatively small fire into one of major proportions with flame and spraying oil reaching an estimated height of 80 feet.

A report is being prepared on these tests, which will be publicized in the near future.

A. M. de Bellis: The discussions reflect a great deal of interest in plant modernization.

Similar points having been raised by

various discussers, a general reply seems to be in order, supplemented by some answers to specific questions.

All the discussers agree in principle as to the necessity of some form of station modernization in order to safeguard against major shutdowns.

The question has been raised, however, of the necessity of extensive segregation of the switching equipment, provided circuit breakers of a modern design and some method of relay protection were used.

It is difficult, of course, to reply very specifically to this general query. There are probably no two cases of station design which lend themselves to exactly the same treatment and I think that for each individual case, the answer to how far to go in station sectionalization and reconstruction must be left to the judgment of the engineers charged with the responsibility of protecting against service interruptions and of justifying capital investments. I would like to point out, however, that operating experience is responsible to a great extent for the present trend toward extensive sectionalization of the electrical equipment in a switch gallery.

During the last 15 years approximately 25 major station shutdowns have occurred in this country.

Approximately half of this number were attributed to causes other than circuit-breaker trouble and as a matter of fact practically all of the most spectacular station shutdowns were due to causes other than operating failures of circuit breakers.

Modern oil circuit breakers have indeed a very good operating record and the trend toward the reduction or the elimination of oil in circuit breakers and the installation of bus differential relays are steps in the right direction.

Yet, I think that it would be rash to assert of any modern type of electrical equipment, be it a circuit breaker, a relay, or just a bus, that it represents the last word and that no precautions, such as sectionalization, need be taken to protect against its failure when such a failure might have disastrous results.

In reply to Mr. Reid's questions relative to differential-relay operation, we have no experience with the installation of relay-shunting devices as a means of by-passing the direct current on through short circuits.

The relay pickup for through faults varies from 10 per cent to 15 per cent of the maximum through-fault current.

I agree with Mr. Field's suggestion of the desirability of providing, whenever possible, some means of relieving the pressure resulting from equipment failures.

The questions raised by Mr. Fugill regarding the relative merits of various types of bus construction are interesting and very much to the point.

Ordinarily, I think it would be logical to expect to have to pay a higher price for a type of equipment which, as Mr. Fugill agrees, offers several advantages over the more conventional type of metal-enclosed equipment.

In the case of Waterside and Sherman Creek, however, comparative estimates based on actual construction costs and on manufacturers' quotations indicated a lower over-all cost for the type of bus construction used as compared to the cost of conventional types of masonry construction or metal-enclosed equipment.

Probably the most important factors affecting the over-all cost of a bus structure are the amount and type of labor required.

The bus structure developed for our stations consists of a simplified type of design which reduces to a minimum such labor requirements in both the manufacture as well as the installation of the equipment.

I agree with Mr. Fugill's reasoning for keeping the number of insulators to a minimum, particularly if Mr. Fugill refers to the conventional type of insulator design.

Mr. Fugill's statement regarding the usefulness of two of the insulators used at each point of support in our bus structures is not quite correct.

I think it is generally recognized that mechanical forces of great magnitude may be caused during short circuits by mechanical oscillations set up in the busses and bus supports which are mechanically clamped to the busses and which are subject to cantilever stresses.

These cantilever stresses may be caused not only by electromagnetic forces acting on busses or at bus taps and bends but also by electromagnetic forces caused by line to ground faults or by the longitudinal tension set up along the busses and stressing the insulators in a direction at right angles to that of the electromagnetic forces.

One of our major considerations in the development of the bus structure was to obtain a type of bus support which would not be subjected to cantilever stresses.

No heads being used with the porcelain insulators, it is obvious that either three or four insulators are required at each point of support to hold the busses in place.

Porcelain insulators of simple and standardized design and of very low cost compared to that of the conventional type of insulator are used.

This arrangement, I think, removes guesswork from the design and application of bus supports and by working the porcelain the way it should be worked, that is in compression, not only increases the safety factor of the entire bus structure but results in a more rational and more economical use of this material.

Mr. Fugill's assumption that the bus insulation would be carried through the insulator heads is, of course, correct. In our case, however, as I have already stated, no insulator heads are used.

As regards the degree of safety of this type of metal-enclosed bus, I would refer Mr. Fugill to that part of my paper which describes the operating experience in the case of a fault during the early stages of the Waterside installation.

I may add that this type of bus design was chosen primarily because, in our opinion, it offers marked advantages as regards service reliability and safety to personnel.

We share the opinion of Mr. Hobbs and Mr. Summerhayes that further consideration of the fault-bus scheme of protection, particularly in connection with metal-enclosed equipment, is warranted.

We fully agree with Mr. Langstaff and other discussers that the supply systems for station auxiliaries, generator excitation, and controls are of paramount importance and that in plant modernization programs they should not be regarded merely as an auxiliary or secondary step.

D. W. Taylor: In regard to Mr. Reid's first question, we have had no experience with the operation of low-resistance high-reactance iron-core reactors connected across the coils of differential relays to by-pass the direct current. As to his inquiry concerning the ratio between the minimum current setting on the differential bus relays and the maximum through fault current, we have used ratio differential relays of the *CA* type, probably for the reason that prompted Mr. Reid's question. The minimum current setting varies with the load or through current and our bus relays are set for 40 per cent unbalance.

Commenting on the masonry reactor cubicles, Mr. Hobbs stated that metal enclosures have been used in many installations. The elimination of the heating problems was not the only reason for the adaption of the masonry cubicles, for in addition they were more economical than metal enclosures, both as to first cost and maintenance.

The masonry cell and bus structures, in answer to Mr. Fugill's inquiry, are in general without any reinforcing rods. In a few large horizontal slabs, rods are necessary, and in these cases, the rods are well separated from each other, run in one direction only, and have several inches of concrete between outside steel or other structures. Building steel and building reinforcing is grounded at numerous points, conduit is grounded at its termination in the cell structure, and the conduit banks tied together and grounded to the building steel at frequent intervals. Oil circuit breakers and instrument transformers are heavily grounded; the bases of all disconnecting switches are grounded; the bases of lead and bus supports are not grounded. However, approximately 75 per cent of the leads consist of fully insulated tubing on porcelain supports, and this includes leads in the instrument-transformer and disconnecting-switch compartments. The horizontal busses are bare copper, in separate compartments free of any apparatus. Mr. Gay has spoken of the insulating value of properly constructed concrete. The value of this insulation was shown in the last few years when at Marion generating station two electrocuted rats and one cat were found in the bus structure, none causing a fault. As rodents are almost always present in stations, the insulated bus structure is beneficial in this respect. In regard to stray fault currents, a heavy interconnected grid or station counterpoise, that joins all apparatus, conduit, and building steel to all station neutrals, so that no great potential gradients are obtained under fault conditions, is of importance. Where troubles have been experienced in the past, we believe the difficulty can be traced to a lack of such an interconnecting grid. If we were constructing a new station of similar character to Essex, we would probably use outdoor switching; however, should indoor structures be necessary, our years of satisfactory service with the insulated type of masonry structure, particularly as a fire barrier, or a second line of defense, would probably cause the adaption of this type of structure. We would probably use completely insulated bus.

Mr. Frisby points out that with the improved reliability of modern oil circuit breakers, the extensive rebuilding of structures and erection of fire barriers may not be justified. In the case of the Essex generating station, the main breakers could not be rebuilt for sufficient interrupting capacity; neither could they be replaced, breaker for breaker, due to insufficient space. In order to install modern breakers of the proper interrupting capacity, the removal of large portions of the existing bus structure would have been necessary, with the accompanying rerouting and reconnecting of leads, which in itself amounted to an extensive rebuilding job, but to limit this to just providing space for the larger breakers would have resulted in excess footage of bus and leads, and close clearances and crowded arrangements in many portions of the station. In addition, as mentioned by Mr. Noest, relay schemes do not always function, and breakers may jam or small parts break. Also, burning insulation on cables or leads may cover the insulators with soot and smoke, and fumes fill the switch galleries, so that even with breakers of adequate interrupting capacity and modern reliability, it was thought that a second line of defense, in the form of segregation and barrier walls, was essential.

H. E. Strang and **W. M. Hanna:** Mr. Reid has asked questions regarding bus differential relays which because of variation in conditions cannot be answered in general terms. It is necessary that the settings must be below the minimum secondary current for a short circuit in the protected area considering both the current available and the errors in the current transformers. The setting must also be above the error in the current transformer carrying the maximum current to a fault outside the areas. This usually means using exceptionally good current transformers, delaying the relaying until the transient producing errors in the current transformers is over, or blocking the relays temporarily if excessive error exists. His suggestion of a high-reactance low-resistance coil to shunt the d-c component is interesting because of the well-known fact that this component cannot be accurately reproduced in the secondary circuit. The real trouble caused by this component is the saturation produced by it in the current-transformer core, which produces errors in the ratio of the a-c component. Saturation also introduces harmonics in the secondary current and a relay is available which shunts these harmonics through a restraining coil which acts to prevent relay operation due to current-transformer saturation. The failure of the current transformer to reproduce accurately the d-c component may be of less concern with this type of relay.

Mr. Gay's tests on bus insulators mounted on concrete are very interesting and we believe show that the probability of getting a short circuit to ground through foreign objects such as rats is reduced, by not grounding the base of the insulator. However, his tests did show progressively increasing arcing after an arc had started. Any arc started by a transient overvoltage condition therefore would probably hang on and increase. It seems to us then that it is well worth while to ground the insulator bases to improve relaying and provide a positive path to ground so the short-circuit currents will not wander in devious and destructive ways on its road to ground.

Mr. Trice's comment that reliability of service should have been given more consideration is important. In fact, it was the intent of the authors that all other points covered by the paper were to attain this end.

Mr. Trice also points out that if no arc exists, photoelectric protection will not work, which is true. He points out that this type of fault can occur if an operator forgets to open the ground switch after working on the bus. We believe that an operator in energizing a bus section after a shutdown will do so with his eyes on his instruments and will trip the breaker if trouble is indicated. As a fault not involving an arc is not so damaging as an arcing fault the decay due to manual instead of automatic clearing should not be serious in this case.

Values of the Bessel Functions ber x and bei x and Their Derivatives

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THE FUNCTIONS ber x and bei x and their derivatives are frequently used in electrical-engineering problems connected with heavy conductors and with wires at radio frequencies. For instance, the current distribution and the resistance loss in a round conductor, or in a coreless induction furnace, are often computed by means of these functions.

One of the most widely used tables of values is that published by A. G. Webster.[1] This covers the range of $x = 0$ to 10, at intervals of 0.1. The polar forms of these quantities were given in the "Report of the British Association for the Advancement of Science," 1923, page 293, by A. E. Kennelly and P. L. Alger.[2]

In the present paper there are given tables for $x = 0$ to 20, at intervals of 0.1 to five significant figures.

When more than five significant figures are desired, see references 1 to 4. For a table at intervals 0.01 of x, for $x = 0$ to 6, with four significant figures, see reference 5.

The new values for the tables in the present paper were computed by students at Massachusetts Institute of Technology, who were engaged in work under the National Youth Administration during the past three years. Those who did a considerable amount of work in this project include H. A. Burr, D. R. Erb, D. Gleason, L. A. King, J. J. Novak, A. Rosenfeld, and H. Schaevitz.

Precautions against errors have been taken by checking the work thoroughly and also by using differences. The computations were carried out to more places than have been tabulated. The changes in bei$'$ x for $x = 6.5$ to 10 given by H. G. Savidge[6] have been included, with the resulting values of the polar forms. Note that in reference 1, bei$'$ 3.7 should be 0.131 486 760 and bei 8.9 should be $-28.002\,867\,538$.

Since one of the results most frequently required in this type of work is the effective resistance of a round wire, it may be noted that this has been very completely tabulated in reference 7.

It is desired to acknowledge valuable suggestions from Doctor L. J. Comrie, recently secretary of the committee on calculation of mathematical tables of the British Association for the Advancement of Science.

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Table I

x	ber x	bei x	ber' x	bei' x	x	ber x	bei x	ber' x	bei' x
0	1.00000	0	0	0	8.0	20.974	−35.017	38.311	−7.6603
.1	1.00000	.002500	−.0000625	.050000	8.1	24.957	−35.667	41.353	−5.2855
.2	.99998	.010000	−.0005000	.099999	8.2	29.245	−36.061	44.415	−2.5296
.3	.99987	.022500	−.0016875	.14999	8.3	33.840	−36.159	47.472	.63410
.4	.99960	.039998	−.004000	.19997	8.4	38.738	−35.920	50.492	4.2318
.5	.99902	.062493	−.007812	.24992	8.5	43.936	−35.298	53.442	8.2895
.6	.99798	.089980	−.013498	.29980	8.6	49.423	−34.246	56.281	12.832
.7	.99625	.12245	−.021433	.34956	8.7	55.187	−32.714	58.967	17.883
.8	.99360	.15989	−.031989	.39915	8.8	61.210	−30.651	61.451	23.465
.9	.98975	.20227	−.045537	.44846	8.9	67.469	−28.003	63.682	29.598
1.0	.98438	.24957	−.062446	.49740	9.0	73.936	−24.718	65.601	36.299
1.1	.97714	.30173	−.083082	.54581	9.1	80.576	−20.724	67.145	43.583
1.2	.96763	.35870	−.10781	.59352	9.2	87.350	−15.976	68.246	51.460
1.3	.95543	.42041	−.13697	.64034	9.3	94.208	−10.412	68.831	59.936
1.4	.94008	.48673	−.17093	.68601	9.4	101.10	− 3.9693	68.821	69.012
1.5	.92107	.55756	−.21001	.73025	9.5	107.95	3.4106	68.132	78.684
1.6	.89789	.63273	−.25454	.77274	9.6	114.70	11.787	66.674	88.940
1.7	.86997	.71204	−.30484	.81310	9.7	121.26	21.218	64.353	99.763
1.8	.83672	.79526	−.36118	.85093	9.8	127.54	31.758	61.070	111.12
1.9	.79752	.88212	−.42384	.88574	9.9	133.43	43.459	56.720	122.99
2.0	.75173	.97229	−.49307	.91701	10.0	138.84	56.370	51.195	135.31
2.1	.69869	1.0654	−.56906	.94418	10.1	143.63	70.534	44.384	148.03
2.2	.63769	1.1610	−.65200	.96661	10.2	147.67	85.987	36.171	161.08
2.3	.56805	1.2585	−.74202	.98361	10.3	150.81	102.76	26.438	174.38
2.4	.48905	1.3575	−.83920	.99443	10.4	152.90	120.87	15.066	187.82
2.5	.39997	1.4572	−.94358	.99827	10.5	153.77	140.32	1.9344	201.30
2.6	.30009	1.5569	−1.0551	.99426	10.6	153.23	161.12	−13.076	214.69
2.7	.18871	1.6557	−1.1738	.98149	10.7	151.09	183.25	−30.083	227.85
2.8	.065112	1.7529	−1.2993	.95897	10.8	147.14	206.68	−49.202	240.59
2.9	−.071368	1.8472	−1.4314	.92566	10.9	141.17	231.35	−70.544	252.75
3.0	−.22138	1.9376	−1.5698	.88048	11.0	132.95	257.21	−94.212	264.12
3.1	−.38553	2.0228	−1.7141	.82230	11.1	122.25	284.14	−120.30	274.46
3.2	−.56438	2.1016	−1.8636	.74992	11.2	108.81	312.06	−148.90	283.54
3.3	−.75841	2.1723	−2.0177	.66214	11.3	92.383	340.80	−180.08	291.07
3.4	−.96804	2.2334	−2.1755	.55769	11.4	72.707	370.21	−213.89	296.76
3.5	−1.1936	2.2832	−2.3361	.43530	11.5	49.517	400.08	−250.37	300.29
3.6	−1.4353	2.3199	−2.4983	.29366	11.6	22.543	430.18	−289.55	301.32
3.7	−1.6933	2.3413	−2.6608	.13149	11.7	−8.4832	460.25	−331.41	299.48
3.8	−1.9674	2.3454	−2.8222	−.052527	11.8	−43.828	489.97	−375.92	294.37
3.9	−2.2576	2.3300	−2.9807	−.25965	11.9	−83.753	519.00	−423.01	285.58
4.0	−2.5634	2.2927	−3.1347	−.49114	12.0	−128.51	546.95	−472.57	272.67
4.1	−2.8843	2.2309	−3.2818	−.74817	12.1	−178.34	573.38	−524.46	255.18
4.2	−3.2195	2.1422	−3.4200	−1.0319	12.2	−233.48	597.82	−578.51	232.62
4.3	−3.5679	2.0236	−3.5465	−1.3433	12.3	−294.11	619.72	−634.46	204.50
4.4	−3.9283	1.8726	−3.6588	−1.6833	12.4	−360.42	638.51	−692.03	170.30
4.5	−4.2991	1.6860	−3.7537	−2.0526	12.5	−432.56	653.56	−750.87	129.49
4.6	−4.6784	1.4610	−3.8280	−2.4520	12.6	−510.62	664.17	−810.58	81.534
4.7	−5.0639	1.1946	−3.8782	−2.8818	12.7	−594.69	669.61	−870.67	25.889
4.8	−5.4531	.88366	−3.9006	−3.3422	12.8	−684.75	669.07	−930.59	−37.992
4.9	−5.8429	.52515	−3.8911	−3.8331	12.9	−780.78	661.72	−989.72	−110.65
5.0	−6.2301	.11603	−3.8453	−4.3541	13.0	−882.65	646.64	−1047.3	−192.61
5.1	−6.6107	−.34666	−3.7589	−4.9046	13.1	−990.17	622.87	−1102.7	−284.38
5.2	−6.9803	−.86584	−3.6270	−5.4835	13.2	−1103.1	589.42	−1154.8	−386.45
5.3	−7.3344	−1.4443	−3.4445	−6.0892	13.3	−1221.0	545.22	−1202.7	−499.28
5.4	−7.6674	−2.0845	−3.2064	−6.7199	13.4	−1343.4	489.19	−1245.3	−623.27
5.5	−7.9736	−2.7890	−2.9070	−7.3729	13.5	−1469.8	420.18	−1281.5	−758.77
5.6	−8.2466	−3.5597	−2.5410	−8.0454	13.6	−1599.5	337.04	−1309.9	−906.08
5.7	−8.4794	−4.3986	−2.1024	−8.7336	13.7	−1731.5	238.57	−1329.2	−1065.4
5.8	−8.6644	−5.3068	−1.5855	−9.4333	13.8	−1865.0	123.55	−1337.7	−1236.9
5.9	−8.7937	−6.2854	− .98438	−10.139	13.9	−1998.7	−9.210	−1333.9	−1420.5
6.0	−8.8583	−7.3347	−.29308	−10.846	14.0	−2131.3	−160.94	−1316.1	−1616.1
6.1	−8.8491	−8.4545	.49429	−11.547	14.1	−2261.3	−332.82	−1282.3	−1823.5
6.2	−8.7561	−9.6437	1.3835	−12.235	14.2	−2387.1	−526.02	−1230.7	−2042.3
6.3	−8.5688	−10.901	2.3802	−12.901	14.3	−2506.8	−741.65	−1159.1	−2272.0
6.4	−8.2762	−12.223	3.4899	−13.536	14.4	−2618.2	−980.75	−1065.4	−2511.6
6.5	−7.8669	−13.607	4.7174	−14.129	14.5	−2719.1	−1244.3	−947.37	−2760.4
6.6	−7.3287	−15.047	6.0675	−14.670	14.6	−2806.8	−1533.1	−802.69	−3016.9
6.7	−6.6492	−16.538	7.5442	−15.146	14.7	−2878.6	−1847.9	−628.96	−3279.9
6.8	−5.8155	−18.074	9.1510	−15.543	14.8	−2931.6	−2189.2	−423.74	−3547.4
6.9	−4.8146	−19.644	10.891	−15.847	14.9	−2962.3	−2557.4	−184.56	−3817.5
7.0	−3.6329	−21.239	12.765	−16.041	15.0	−2967.3	−2952.7	91.056	−4087.8
7.1	−2.2571	−22.848	14.774	−16.109	15.1	−2942.8	−3374.9	405.59	−4355.5
7.2	−.67370	−24.456	16.918	−16.033	15.2	−2884.8	−3823.6	761.47	−4617.5
7.3	1.1308	−26.049	19.194	−15.792	15.3	−2789.0	−4298.1	1161.1	−4870.4
7.4	3.1695	−27.609	21.600	−15.367	15.4	−2651.0	−4797.3	1606.6	−5110.3
7.5	5.4550	−29.116	24.130	−14.736	15.5	−2466.1	−5319.6	2100.3	−5332.7
7.6	7.9994	−30.548	26.777	−13.875	15.6	−2229.3	−5863.1	2644.1	−5533.0
7.7	10.814	−31.882	29.532	−12.763	15.7	−1935.5	−6425.3	3239.6	−5705.8
7.8	13.909	−33.092	32.382	−11.373	15.8	−1579.6	−7003.1	3888.3	−5845.4
7.9	17.293	−34.147	35.314	−9.6806	15.9	−1156.1	−7593.0	4591.3	−5945.6

Table I—Continued

x	ber x	bei x	ber′ x	bei′ x
16.0	−659.50	− 8190.7	5349.3	−5999.5
16.1	− 84.364	− 8791.2	6162.6	−6000.0
16.2	574.85	− 9388.7	7030.8	−5939.2
16.3	1323.6	− 9976.7	7953.1	−5808.8
16.4	2167.2	−10548	8927.9	−5600.2
16.5	3110.8	−11094	9952.9	−5303.9
16.6	4159.4	−11605	11025	−4910.4
16.7	5317.2	−12072	12140	−4409.5
16.8	6588.5	−12483	13292	−3790.6
16.9	7976.7	−12826	14476	−3043.0
17.0	9484.5	−13087	15683	−2155.5
17.1	11114	−13252	16905	−1116.9
17.2	12866	−13305	18132	84.10
17.3	14740	−13230	19351	1459.0
17.4	16735	−13007	20550	3018.9
17.5	18849	−12619	21711	4774.9
17.6	21076	−12045	22819	6737.5
17.7	23410	−11265	23854	8916.7
17.8	25843	−10255	24795	11322
17.9	28365	−8992.4	25618	13961
18.0	30962	−7454.3	26298	16841
18.1	33619	−5616.0	26807	19968
18.2	36317	−3452.4	27115	23345
18.3	39034	−938.55	27189	26975
18.4	41746	1950.9	26993	30857
18.5	44423	5241.1	26492	34987
18.6	47033	8956.4	25645	39360
18.7	49539	13121	24411	43967
18.8	51901	17757	22745	48793
18.9	54072	22886	20602	53821
19.0	56003	28527	17934	59029
19.1	57640	34697	14691	64390
19.2	58921	41409	10823	69871
19.3	59782	48674	6279.0	75433
19.4	60152	56497	1006.0	81030
19.5	59957	64879	−5048.2	86609
19.6	59115	73816	−11935	92111
19.7	57540	83297	− 19706	97468
19.8	55143	93303	−28411	102600
19.9	51826	103810	−38095	107430
20.0	47489	114780	−48803	111860

Table II

$$\text{ber}\, x + i\, \text{bei}\, x = J_0(xi^{3/2}) = M(\cos\theta + i\sin\theta)$$

x	M	θ Degrees
0	1.0000	0
.1	1.0000	.143
.2	1.0000	.573
.3	1.0001	1.289
.4	1.0004	2.291
.5	1.0010	3.579
.6	1.0020	5.152
.7	1.0037	7.007
.8	1.0064	9.141
.9	1.0102	11.550
1.0	1.0155	14.226
1.1	1.0227	17.160
1.2	1.0320	20.340
1.3	1.0438	23.750
1.4	1.0586	27.373
1.5	1.0767	31.188
1.6	1.0984	35.172
1.7	1.1242	39.299
1.8	1.1544	43.545
1.9	1.1892	47.883
2.0	1.2290	52.290
2.1	1.2741	56.743
2.2	1.3246	61.221
2.3	1.3808	65.708
2.4	1.4429	70.188
2.5	1.5111	74.651
2.6	1.5855	79.090
2.7	1.6665	83.498
2.8	1.7541	87.873
2.9	1.8486	92.213
3.0	1.9502	96.518
3.1	2.0593	100.791
3.2	2.1760	105.032
3.3	2.3009	109.245
3.4	2.4342	113.433
3.5	2.5764	117.599
3.6	2.7280	121.745
3.7	2.8894	125.875
3.8	3.0613	129.991
3.9	3.2443	134.096
4.0	3.4391	138.191
4.1	3.6464	142.279
4.2	3.8670	146.361
4.3	4.1018	150.439
4.4	4.3518	154.514
4.5	4.6179	158.586
4.6	4.9012	162.657
4.7	5.2029	166.726
4.8	5.5242	170.795
4.9	5.8665	174.864
5.0	6.2312	178.933
5.1	6.6197	183.002
5.2	7.0338	187.071
5.3	7.4752	191.140
5.4	7.9457	195.209
5.5	8.4473	199.279
5.6	8.9821	203.348
5.7	9.5523	207.418
5.8	10.160	211.487
5.9	10.809	215.556
6.0	11.501	219.625
6.1	12.239	223.694
6.2	13.026	227.762
6.3	13.865	231.830
6.4	14.761	235.898
6.5	15.717	239.965
6.6	16.737	244.031
6.7	17.825	248.098
6.8	18.986	252.163
6.9	20.225	256.229
7.0	21.548	260.294
7.1	22.959	264.358
7.2	24.466	268.422
7.3	26.074	272.486
7.4	27.790	276.549
7.5	29.622	280.612
7.6	31.578	284.674
7.7	33.666	288.736
7.8	35.896	292.798
7.9	38.276	296.859
8.0	40.818	300.920
8.1	43.531	304.981
8.2	46.429	309.042
8.3	49.524	313.102
8.4	52.829	317.162
8.5	56.359	321.222
8.6	60.128	325.282
8.7	64.155	329.341
8.8	68.455	333.400
8.9	73.049	337.459
9.0	77.956	341.518
9.1	83.199	345.577
9.2	88.799	349.635
9.3	94.782	353.693
9.4	101.17	357.752
9.5	108.00	1.810
9.6	115.30	5.867
9.7	123.10	9.925
9.8	131.43	13.983
9.9	140.33	18.040
10.0	149.85	22.098
10.1	160.02	26.155
10.2	170.88	30.212
10.3	182.49	34.269
10.4	194.91	38.326
10.5	208.17	42.382
10.6	222.35	46.439
10.7	237.51	50.496
10.8	253.71	54.552
10.9	271.02	58.608
11.0	289.54	62.665
11.1	309.33	66.721
11.2	330.48	70.777
11.3	353.10	74.833
11.4	377.28	78.889
11.5	403.13	82.945
11.6	430.77	87.000
11.7	460.33	91.056
11.8	491.93	95.112
11.9	525.71	99.167
12.0	561.84	103.222
12.1	600.48	107.278
12.2	641.79	111.333
12.3	685.97	115.388
12.4	733.21	119.443
12.5	783.74	123.499
12.6	837.77	127.554
12.7	895.56	131.609
12.8	957.36	135.663
12.9	1023.5	139.718
13.0	1094.2	143.773
13.1	1169.8	147.828
13.2	1250.7	151.883
13.3	1337.2	155.937
13.4	1429.7	159.992
13.5	1528.7	164.046
13.6	1634.6	168.101
13.7	1747.9	172.155
13.8	1869.0	176.210
13.9	1998.7	180.264
14.0	2137.3	184.318
14.1	2285.7	188.373
14.2	2444.4	192.427
14.3	2614.2	196.481
14.4	2795.9	200.535
14.5	2990.3	204.589
14.6	3198.2	208.643
14.7	3420.7	212.697
14.8	3658.8	216.751
14.9	3913.5	220.805
15.0	4186.1	224.859
15.1	4477.7	228.913
15.2	4789.8	232.967
15.3	5123.7	237.021
15.4	5481.0	241.075
15.5	5863.4	245.128
15.6	6272.6	249.182
15.7	6710.5	253.236
15.8	7179.1	257.289
15.9	7680.5	261.343
16.0	8217.2	265.397
16.1	8791.6	269.450
16.2	9406.2	273.504
16.3	10064	277.557
16.4	10768	281.611
16.5	11522	285.664
16.6	12328	289.718
16.7	13191	293.771
16.8	14115	297.824
16.9	15104	301.878
17.0	16163	305.931
17.1	17296	309.984
17.2	18508	314.038
17.3	19806	318.091
17.4	21196	322.144
17.5	22683	326.198
17.6	24275	330.251
17.7	25979	334.304
17.8	27804	338.357
17.9	29756	342.410
18.0	31847	346.463
18.1	34085	350.516
18.2	36481	354.570
18.3	39046	358.623
18.4	41791	2.676
18.5	44731	6.729
18.6	47878	10.782
18.7	51247	14.835
18.8	54854	18.888
18.9	58716	22.941
19.0	62851	26.994
19.1	67277	31.047
19.2	72017	35.099
19.3	77091	39.152
19.4	82524	43.205
19.5	88341	47.258
19.6	94570	51.311
19.7	101240	55.364
19.8	108380	59.417
19.9	116020	63.469
20.0	124210	67.522

Table III

$$\text{ber}' x + i\,\text{bei}' x = \frac{d}{dx} J_0(x i^{3/2}) = M(\cos\theta + i \sin\theta)$$

x	M	θ Degrees	x	M	θ Degrees	x	M	θ Degrees	x	M	θ Degrees
0	0	90	5.0	5.8091	228.551	10.0	144.67	69.275	15.0	4088.8	271.276
.1	.050000	90.072	5.1	6.1794	232.534	10.1	154.54	73.310	15.1	4374.3	275.320
.2	.10000	90.286	5.2	6.5745	236.518	10.2	165.09	77.344	15.2	4679.9	279.364
.3	.15000	90.645	5.3	6.9960	240.504	10.3	176.37	81.379	15.3	5006.9	283.409
.4	.20001	91.146	5.4	7.4456	244.492	10.4	188.42	85.414	15.4	5356.9	287.453
.5	.25004	91.790	5.5	7.9253	248.481	10.5	201.31	89.449	15.5	5731.5	291.497
.6	.30010	92.578	5.6	8.4371	252.472	10.6	215.09	93.485	15.6	6132.3	295.542
.7	.35022	93.509	5.7	8.9831	256.465	10.7	229.82	97.521	15.7	6561.4	299.586
.8	.40043	94.582	5.8	9.5656	260.459	10.8	245.57	101.558	15.8	7020.5	303.631
.9	.45077	95.798	5.9	10.187	264.455	10.9	262.41	105.594	15.9	7512.0	307.676
1.0	.50130	97.156	6.0	10.850	268.452	11.0	280.42	109.631	16.0	8038.0	311.721
1.1	.55209	98.655	6.1	11.558	272.451	11.1	299.67	113.669	16.1	8601.0	315.766
1.2	.60323	100.295	6.2	12.313	276.452	11.2	320.26	117.706	16.2	9203.6	319.811
1.3	.65482	102.074	6.3	13.119	280.454	11.3	342.27	121.744	16.3	9848.6	323.856
1.4	.70698	103.991	6.4	13.978	284.457	11.4	365.81	125.782	16.4	10539	327.901
1.5	.75985	106.045	6.5	14.896	288.463	11.5	390.98	129.820	16.5	11278	331.947
1.6	.81358	108.232	6.6	15.876	292.469	11.6	417.89	133.859	16.6	12069	335.992
1.7	.86837	110.551	6.7	16.921	296.477	11.7	446.68	137.898	16.7	12916	340.037
1.8	.92441	112.999	6.8	18.037	300.487	11.8	477.46	141.937	16.8	13822	344.083
1.9	.98192	115.572	6.9	19.228	304.498	11.9	510.38	145.976	16.9	14792	348.129
2.0	1.0412	118.266	7.0	20.500	308.510	12.0	545.59	150.015	17.0	15831	352.174
2.1	1.1024	121.077	7.1	21.858	312.523	12.1	583.25	154.055	17.1	16942	356.220
2.2	1.1659	124.001	7.2	23.308	316.538	12.2	623.52	158.095	17.2	18132	.266
2.3	1.2321	127.030	7.3	24.856	320.554	12.3	666.60	162.135	17.3	19406	4.312
2.4	1.3012	130.161	7.4	26.509	324.571	12.4	712.67	166.175	17.4	20770	8.358
2.5	1.3736	133.387	7.5	28.274	328.589	12.5	761.95	170.215	17.5	22230	12.404
2.6	1.4498	136.701	7.6	30.159	332.608	12.6	814.67	174.256	17.6	23793	16.450
2.7	1.5300	140.098	7.7	32.171	336.628	12.7	871.05	178.297	17.7	25466	20.496
2.8	1.6148	143.570	7.8	34.321	340.649	12.8	931.37	182.338	17.8	27258	24.542
2.9	1.7046	147.110	7.9	36.617	344.670	12.9	995.89	186.379	17.9	29175	28.588
3.0	1.7999	150.713	8.0	39.070	348.693	13.0	1064.9	190.420	18.0	31229	32.635
3.1	1.9011	154.372	8.1	41.689	352.716	13.1	1138.7	194.462	18.1	33427	36.681
3.2	2.0088	158.080	8.2	44.487	356.740	13.2	1217.7	198.503	18.2	35780	40.727
3.3	2.1236	161.832	8.3	47.476	.765	13.3	1302.2	202.545	18.3	38300	44.774
3.4	2.2458	165.622	8.4	50.669	4.791	13.4	1392.6	206.587	18.4	40997	48.820
3.5	2.3763	169.445	8.5	54.081	8.817	13.5	1489.3	210.629	18.5	43885	52.867
3.6	2.5155	173.296	8.6	57.725	12.844	13.6	1592.8	214.671	18.6	46978	56.914
3.7	2.6640	177.171	8.7	61.619	16.871	13.7	1703.5	218.714	18.7	50289	60.960
3.8	2.8227	181.066	8.8	65.779	20.900	13.8	1821.9	222.756	18.8	53834	65.007
3.9	2.9920	184.978	8.9	70.224	24.928	13.9	1948.6	226.799	18.9	57629	69.054
4.0	3.1729	188.905	9.0	74.974	28.957	14.0	2084.2	230.842	19.0	61693	73.101
4.1	3.3660	192.842	9.1	80.049	32.987	14.1	2229.2	234.885	19.1	66045	77.148
4.2	3.5722	196.790	9.2	85.473	37.017	14.2	2384.5	238.928	19.2	70704	81.195
4.3	3.7924	200.744	9.3	91.269	41.048	14.3	2550.5	242.971	19.3	75694	85.242
4.4	4.0274	204.705	9.4	97.463	45.079	14.4	2728.2	247.014	19.4	81036	89.289
4.5	4.2783	208.671	9.5	104.08	49.111	14.5	2918.4	251.057	19.5	86756	93.336
4.6	4.5460	212.641	9.6	111.16	53.143	14.6	3121.9	255.101	19.6	92881	97.383
4.7	4.8317	216.615	9.7	118.72	57.176	14.7	3339.6	259.145	19.7	99440	101.430
4.8	5.1366	220.591	9.8	126.80	61.208	14.8	3572.6	263.188	19.8	106460	105.477
4.9	5.4619	224.570	9.9	135.44	65.242	14.9	3821.9	267.232	19.9	113980	109.525
									20.0	122040	113.572

Aluminum-Nickel-Cobalt Brake Magnets for Watt-Hour Meters

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MEMBER AIEE

IN 1932 a new aluminum-nickel permanent-magnet material was announced. It may desirably contain a small percentage of cobalt and in that form is commercially available in castings from several dependable suppliers. A typical analysis is aluminum 12 per cent, nickel 20 per cent, cobalt 5 per cent, with the rest iron. As compared with previously available materials, it has such a high coercive force as to affect design radically. No discussion of the material itself will be given as this has been presented elsewhere.[1-3]

This article deals with the application of the new alloy to watt-hour meters. Permanency and resistance to the effect of transient magnetic disturbances are the most important considerations. Application of the material requires new features of design and provides radical economies in space and weight. In discussing the design for the new material, a comparison with the present chromium-steel damping unit will be made because much of the knowledge accumulated with this widely used and successful form of magnet can be applied with benefit to the problem of utilizing the high-coercive material.

General Structure

Figure 1 gives typical second-quadrant values of the hysteresis loops of various permanent-magnet materials. Opposite these curves, in the first quadrant are drawn the corresponding energy-product curves for the respective materials. Watt-hour-meter magnets have previously been made of a chromium steel represented by curve *A* while curve *D* is typical for the aluminum-nickel-cobalt material. For watt-hour meters, materials *B* and *C* have been restricted in general use because of high inherent cost. The new damping unit must be different from the old in size, cross section, and shape. No simple substitution of materials is possible.

Figure 2 shows the general form of the chromium-steel damping-magnet unit. It is formed of two C-shaped magnets having a developed length as compared with air-gap length of at least 60 to 1.

Figure 3 shows the general form of the new unit. It has a single horseshoe-shaped magnet on one side of the disk with a soft-iron armature opposite. The ratio of the magnet developed length to the combined length of the two air gaps may be as low as 15 to 1. The disk-gap length in the average unit approximates 0.100 inch. A bidirectional field form with the pole tips approximately 0.35 inch apart is the most effective for acting upon a meter disk and it will be noted that both units produce this form of field but that the new unit is simpler, doing it with only one magnet instead of two. The double gap in the flux circuit is an ideal way of utilizing the high coercive force of the new material. Ninety-five per cent by weight of the constituent elements in the new magnet are inexpensive. Cost resides in the difficulty of fabrication. The small horseshoe magnet is easy to cast. All of the material in it is effectively used. The resultant design, because of its simplicity, becomes economically possible in the watt-hour-meter field where cost is critical.

Figure 4 shows a photograph of the two chromium-steel magnets and the equivalent new magnet taken together. Both units are suitable for damping the moving element of a modern watt-hour meter having a torque range of from 46 to 54 gram-millimeters at rated load and a nominal rated speed of 30 rpm. The weight of the two chromium-steel magnets is 351 grams as compared with 95 grams for the new magnet. This is a reduction in weight of 73 per cent and an even greater decrease could have been made by designing to as close limits for the new material as for the old. Instead of this, the new unit was made with an excess of strength which makes it possible to give it a liberal "knockdown," to be discussed in greater detail, and which also allows a somewhat greater gap for the disk than for the chromium-steel unit, which is an operating and manufacturing advantage.

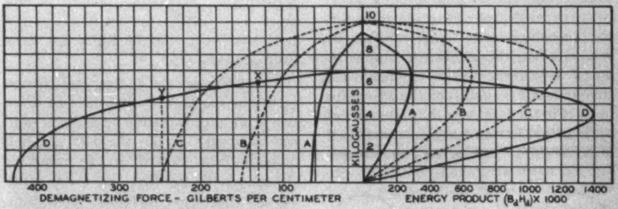

Figure 1. Second-quadrant hysteresis loops and energy-product curves of permanent-magnet materials

A—3.5 per cent chromium steel
B—17.0 per cent cobalt steel
C—36.0 per cent cobalt steel
D—Nickel-aluminum-cobalt steel

The shape of the magnet was chosen after a comparison of the performance of a series of experimental models. It is tapered to give a maximum cross section at the midpoint where both useful and leakage flux must be carried. The slight departure from 90 degrees on the pole faces is for structural convenience in the meter and has no magnetic significance. Figure 5 shows the complete new damping unit on the frame of a single-phase meter of modern design. The magnet and armature are clamped in their relative positions on a small aluminum die casting. An advantage of this is that the gap between magnet poles and armature can be accurately adjusted. Figure 6 is a disassembled view giving a better idea of the clamping washer and screw as well as the temperature-compensating member between the magnet and the clamp washer.

Adjustment as to magnitude of damping (commonly known as full-load adjustment of the meter) is made by forming the armature in three pieces and moving one of them with reference to the other two in

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[1] For all numbered references, see list at end of paper.

order to vary the reluctance of the flux path through the armature. Figure 7 is a view of the full-load unit with the armature, but without the magnet, in two positions—(*a*) with the full-load-adjustment piece all the way out which gives greatest reluctance and least damping, and (*b*) with the full-load-adjustment piece all the way in which, in effect, gives a solid armature and greatest damping. It is easy to make the adjustment bar operable from the front with a screwdriver and it can be depended upon for an adjustment range of ±20 per cent as referred to meter registration. Constructional variations, especially as to adjustment features, will occur to many. These could be made without departing from the general plan in which the horseshoe magnet is used.

Temperature Compensation

For the particular damping unit described in the new material, somewhat less temperature compensation is required than for the chromium-steel unit. Over the range from −20 degrees centigrade to 60 degrees centigrade, the coefficient of the uncompensated damping unit is +0.11 per cent per degree centigrade and refers to percentage meter registration. By compensation this coefficient can be reduced to as low a value as desired. The compensation is applied on the side of the magnet in the form of a thin sheet of one of the alloys having a negative coefficient of permeability with respect to temperature. Such a compensating piece is shown in figure 6 and needs no discussion as its application is generally understood.

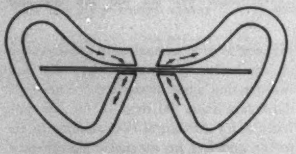


Figure 2. General form of chromium-steel damping unit showing flux paths

Permanency

For many magnet uses a change in strength of a few per cent in a few years would be unimportant. In an instrument magnet it would be highly objectionable. Small changes can be most conveniently detected in terms of meter registration with a magnet unit on a watt-hour meter. Since braking power varies as the square of the flux, small changes in registration, expressed in per cent, will closely approximate double the actual percentage braking-flux changes which cause them. First an example will be given of appreciable-time aging on a group of improperly treated magnets to show that the small changes are readily detected by this method. A group of properly treated chromium-steel units which are substantially nonaging will then be compared with a corrresponding group of the new damping units.

With the familiar chromium-steel meter magnets it has always been necessary to age them artificially by a baking treatment. Curve *A* of figure 8 shows what happened to a group of 20 such chromium-steel magnet units of standard construction but with the baking purposely omitted. This curve and all following aging data are in terms of meter registration as against elapsed time in months. The curve shows the increase in average meter registration for the group over a period of 36 months. Increase in registration means a faster meter and hence less damping or a decrease in magnet strength. After three years the curve flattens out at a two-per-cent increase in registration. Individual meters in the group may increase as much as 3.5 per cent while some of the units age very little or none at all.

About 65 per cent of the total change occurs in the first 12 months and after two years approximately 90 per cent of it has occurred. If the magnets are not properly heat treated or are going to change at all, the first two years after manufacture may, therefore, be considered as an initial critical period which once left behind insures constancy where time is the only consideration.

With the chromium-steel magnet this two-year period can be eliminated by a suitable artificial "aging" process after tempering, which is accomplished by baking. Curve *B* in figure 8 shows the results for another 20 similar magnet units which have been baked for 120 hours at 105 degrees centigrade, which is a standard aging treatment for one manufacturer. The increase in average registration of 0.15 per cent over the period of three years is so small as to leave doubt as to whether limitations in the methods of measurement may not be the cause rather than any real magnet change.

Comparison With New Material

Data are most conveniently presented on the basis of the initial two-year critical period although some of the new units have been on test three years or longer and observations on many units will be continued for a long time.

Table I presents the critical 24-month-initial-period results for three groups of meters. Group *A* is for the same 20 meters used in determining the upper curve of figure 8. Group *B* is for the properly treated 20 chromium-steel units comprising the lower curve of figure 8. Group *C* is for 20 of the new aluminum-nickel-cobalt magnets. Units in all groups are unselected.

It can be seen that there is little to choose, as regards permanency, between either the properly treated chromium-steel unit or the unit of the new material. Both are perfect within the limits of measurement. It must be remembered that the variations include changes which could occur from all possible contingencies, such, for example, as a change in torque of an electromagnet driving unit. They also include the inevitable characteristic errors of the type of measurement involved as well as personal error. A laboratory wattmeter with a clock-controlled timing circuit was used throughout the tests.

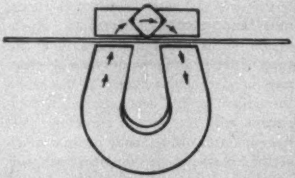


Figure 3. General form of new unit showing flux paths

Table I has its limitations in picturing the minute variations which it is necessary to try to detect so that figure 9 is given to show the performance of another small group of five new units, this time over a period of 30 months. The variations appear large because of the choice of scales but everything shown is happening within a zone less than one-per-cent wide. Although the variations are annoying, they do not preclude consideration of a number of meters together and thus, from averages, a more reliable result may be obtained than with one unit alone. By testing a large number of magnets it is possible to get more representative results and to check samples from different heats and from various sources of supply. This was consistently done.

From a study of the available experimental data, only a small portion of which has been included, it seems clear that within the first two or three years the change in the new damping units is too small to detect. There is no reason to suppose that there will be any change after that time.

Appendix I details the composition, heat treatment, and dimensions of the new units on which permanency data are given. Appendix II gives the composition, heat treatment, and processing of the chromium-steel magnets on which permanency data are given.

Effect of Baking

One reason advanced for the change in untreated chromium steel is that the final operation in hardening is quenching from a high temperature, which leaves portions of the magnet under strain. These strains increase the magnetic qualities but they tend to relieve themselves gradually over a period of time, causing slight weakening of the magnet. As shown in figure 8, curve *A* they are substantially all relieved in three years and 90 per cent of them in two years after the tempering process. The amount of strain, and possible magnetic change, left in a magnet depends to an extent upon the forging process and hence upon shape, but even a straight bar is subject to some change. Curve *A* of figure 8 holds for the shape of chromium-steel magnet shown in figure 2. The long bake at 105 degrees centigrade stabilizes the material by accelerating the changes so that they are complete in 120 hours. It makes no difference whether this bake is given the magnets before or after magnetization. In practice it is convenient to give it before.

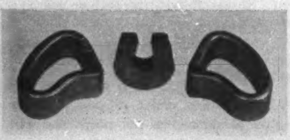


Figure 4. View of two chromium magnets and equivalent new magnet taken together

It could be argued that the new magnetic material is also full of strains and that a similar or even more severe bake would be required to stabilize it. To investigate this, baking tests were made on three chromium-steel bars and three bars of the aluminum-nickel-cobalt material.

Values of coercive force and residual flux were measured for all samples initially and at intervals during a bake lasting 1,000 hours at 105 degrees centigrade. For the chromium steel, coercive force decreased 9.5 per cent and residual flux increased 4.9 per cent as determined from average values for the three samples. Nearly all this change occurred in the first 200 hours. For the new aluminum-nickel-cobalt steel, coercive force decreased only 1.1 per cent and residual flux changed only 0.4 per cent. These latter values are so small as to throw doubt on whether any change really occurred because of limitations in the accuracy of measurement. This test indicates that no reasonable amount of baking at as low a temperature as 105 degrees centigrade will have any effect on the new alloy. Various other baking cycles and temperatures were tried, ranging as high as 315 degrees centigrade for 38 hours and 150 degrees centigrade for 120 hours, all without having any detectable effect on stability. These results were suspected from the start in that the new magnet is a product of precipitation hardening instead of rapid quenching from a high temperature and in addition as a last step, the makers hold it in a furnace at a 1,250 degrees Fahrenheit for 15 minutes. It is possible that even this latter heat treatment is not necessary for time stability, but additional exhaustive tests would be necessary to determine this. In the meantime, in view of the small added expense of the 1,250-degree treatment, it should be continued for instrument magnets.

Magnetizing

Magnets as received from the foundry are cleaned by tumbling and sandblasting. Each magnet, after tumbling, is individually "rung" by hitting it lightly with a small hammer and any cracks or flaws can be detected by the sound. A protective coating, such as enamel, can be omitted as the new material falls within the classification of corrosion-resistant alloys. Although the magnets are brittle, a negligible loss through breakage is suffered during the tumbling process. The elimination of paint on magnets is an operating advantage as difficulty has been experienced in the past in getting it to stick to magnets over a long period of time.

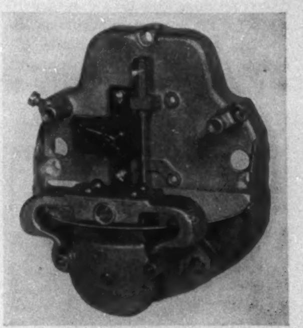


Figure 5. View of complete new damping unit on frame of a single-phase meter

The magnets are magnetized by placing them on a magnetizing fixture and applying at least 5,000 ampere turns per inch acting through their flux circuit to saturate them thoroughly. In production it is desirable to make this current more than sufficient, even by twice the amount, and to keep the apparatus cool by allowing the current to flow for only a fraction of a second.

When the magnet is taken off the magnetizing apparatus, a large gap is interposed in its flux circuit and this on the average magnet has the effect of bringing the material to approximately the point marked *X* on curve *D* of figure 1. Later on by an a-c demagnetizing process or "knockdown" the material may be still further brought down to a point which may be represented at about *Y* on curve *D*. The amount of additional a-c "knockdown" to reach the point *Y* may be set at any desired minimum depending upon the liberality of design in the unit. Since the magnet under discussion is tapered and of varying cross section, the points *X* and *Y* of figure 1 while approximately correct for the average cross section of the average unit, should be considered as subject to some variation.

Table I. Natural Aging of Magnet Units Over an Initial 24-Month Period

Group	Description	Change From Initial Meter Registration in Per Cent		
		Maximum Slow	Maximum Fast	Group Average
A	Untreated chromium-steel units	−0.20	+3.25	+1.87
B	Chromium-steel units baked 120 hours at 105 deg C	−0.20	+0.70	+0.15
C	Aluminum-nickel-cobalt units, various treatments	−0.27	+0.59	+0.14

Twenty magnet units are in each group.

The maximum slow and maximum fast values are those found for the extreme individual units in each group. An increase in meter registration would indicate an apparent decrease in damping unit strength.

A-C "Knockdown"

The value of an a-c "knockdown" in stabilizing instrument magnets has been discussed before.[5] The unusually large amount of knockdown in gilberts per centimeter resulting from the a-c demagnetization for the average aluminum-nickel-cobalt magnet can be seen in figure 1 as the abscissa of point Y minus the abscissa of point X, or 120 oersteds. The general effect is to "immunize" the magnet to the susceptibility of further weakening from another demagnetizing force when subsequently encountered in service up to as great a value as the knockdown force. In addition to this protective action against magnetic disturbances, the knockdown has other stabilizing tendencies. As an example, a meter equipped with one of the new magnet units with no knockdown may gain in registration as much as one per cent in the first 24 hours. With knockdown, no change can be detected. Also, as will be seen, adequate knockdown insures stability of the magnet regardless of the effect of temperature cycles.

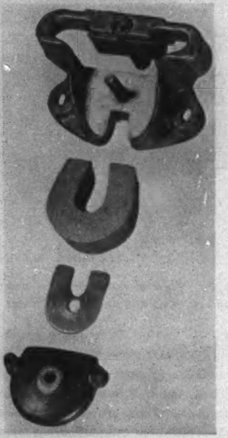


Figure 6. View of disassembled magnet unit

Effect of Temperature Cycles

Watt-hour meters, especially with modern outdoor installations, are subject to continued cycles of heat and cold. These may affect magnet strength unless proper precautions are taken in the magnet processing. Tests were made on this subject with results too voluminous to record in detail but it is desirable to summarize the conclusions. A very severe temperature cycle was used from −40 degrees centigrade to 90 degrees centigrade, which exceeds anything encountered in actual service.

(*a*). Chromium steel magnet units, even though properly aged and given an ample a-c "knockdown," may weaken by as much as one per cent (expressed in terms of meter registration) as a result of three temperature cycles. Ninety per cent of this weakening occurs as a result of the first cycle and more specifically as a result of the first heating. Succeeding cycles above three have no effect. For this reason it has been standard practice to give chromium-steel units an additional short bake at 105 degrees centigrade as a last step in their processing. This is in addition to the long bake for artificial-aging purposes. This latter bake takes away the effects of future temperature cycles.

(*b*). The new high-coercive magnets, if given no "knockdown," will weaken as a result of temperature cycles. To determine this, a number of the new units were magnetized with the armature in place and an iron vane occupying the normal disk-gap space. After assembly this vane was pulled out. Under these conditions the group of units averaged 1.8 per cent increase in meter registration as a result of three temperature cycles. As with the chromium steel, the first cycle did the greater part of the damage and additional cycles beyond three had no effect.

(*c*). Different groups of the new magnets with the proper a-c "knockdown" were then tested by passing them through not less than three temperature cycles. No change in braking flux could be observed as a result of such temperature cycles. If a change had occurred, it could have been eliminated by an additional bake as with the chromium-steel units but such a bake is not necessary providing that the a-c knockdown is properly applied. By proper application of the a-c knockdown is meant that at least one-half of it must be applied by passing the alternating current through the inside of the horseshoe with an armature in place so that all portions of the magnet flux circuit are subjected to the demagnetizing force.

(*d*). As a matter of academic interest, tests were made to see if temperature cycles applied to the magnets before magnetization would immunize them from the effects of such cycles after magnetization. The results indicated that the previous temperature cycles were of little use. This result is in contrast to the condition with respect to the "aging" bake which does just as much good before magnetization as after.

Effect of Magnetic Transients on Meters

Watt-hour meters like other electrical apparatus suffer from undesirable magnetic transients. Weakened magnets are the result of such disturbances when they are great enough to overcome the immunity of the magnets conferred by their "knockdown."

Three sources of magnetic transients can be listed:

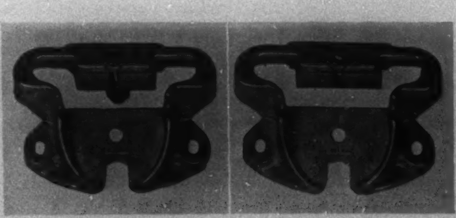
(*a*). Surges through the potential coil of the meter as a result of overvoltage or of lightning.

(*b*). Surges through the current coil as a result of either short circuits or of lightning.

(*c*). Current surges through any wire passing near, below, or in back of the meter such as a neutral wire.

Disturbances under (*a*) are least capable of damaging the magnets. The inductance of the meter potential coil is high and repeated surge tests have demonstrated that with even a moderately steep wave front, a breakdown will occur to ground in the case of lightning before enough current can be forced through the coil to damage the magnets.

Under (*b*) it is possible to weaken the chromium-steel magnets of a good modern meter slightly but only under the most extreme short circuits of from 5,000 to 7,000 amperes, peak value. With the usual meter these values can be obtained only in the short-circuit laboratory as the impedance of modern distribution circuits will not allow such currents. Furthermore, power surges of such high value cannot be obtained in service on the usual single-phase meter as used with 30- or 60-ampere fuses. The fuse opens the circuit before these extreme current values are attained. If a lightning surge, instead of a-c power current acts on the current windings, its steep wave front tends to make it flash across the coil rather than through it, if the current value is high,



(*a*) (*b*)

Figure 7. Unit without magnet, in two positions

(*a*)—Minimum damping

(*b*)—Maximum damping

and thus fall under (*c*). Magnet weakening is possible under (*b*) but as a factor it is unimportant as compared with the next classification.

Under (*c*) the current surge may be caused as a result of lightning. It usually is in the neutral wire of a three-wire grounded-neutral system although it could be in one of the outside wires on occasions. All bad lightning disturbances result in condition (*c*) in that if the surge is strong enough, most of it flashes over the coils in the meter and goes directly to ground along some wire passing near the meter. Condition (*c*) can be simulated in the surge laboratory by a straight wire behind and near the meter. In contrast with the first two cases, magnets can be damaged with severe surges. Condition (*c*) is the most severe and consequently comparative tests were made under this condition.

Resistance to the Effect of Surges

A number of meters were tested to determine the relative resistance to the effect of surges under condition (*c*). To do this a circular loop was used which was 40 inches in diameter and had three turns. By placing a meter close to and on one side of the loop, a vertical straight conductor behind the meter could be closely approximated. Placing the meter close to and at the bottom of the loop simulated a straight horizontal conductor behind the meter.

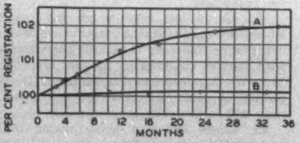


Figure. 8. Natural aging curve on chromium-steel units over three years

(*A*)—Untreated (*B*)—Treated

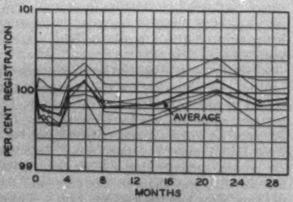


Figure 9. Five aluminum-nickel-cobalt units over 30 months

Mean effective ampere turns in the loop could be adjusted from 1,500 to 15,000. Duration of surges in the loop was controlled by blowing a fuse of predetermined size and oscillograph records were taken on each surge. Duration of surges was in no case less than three full cycles. Demagnetizing effect depends upon crest values but for convenience results are here reported in terms of root-mean-square values.

As a result of the tests on meters equipped with the new aluminum-nickel-cobalt damping units, it was found that the least resistant units would withstand a-c values of 13,000 ampere turns vertically and directly behind the meter without being affected. Some of the stronger units were able to withstand up to 15,000 ampere turns. The wire vertical and behind the meter, for which the results are given, proved to be more damaging than horizontal, although tests were made in both positions, the horizontal test being made first.

On a few meters having chromium-steel magnets, the surge-current ampere turns that could be withstood without damage ranged from 2,300 to 3,500. It should be realized that these are laboratory surge values expressed in root-mean-square figures and that even the lower amounts as measured for the chromium units are satisfactory in normal service.

Effect of Abnormal Surges on Chromium Steel Units

More contrasting laboratory tests in determining the merit of the improved damping unit are possible by subjecting a few meters having magnets of the chromium-steel variety to surges of 13,000 ampere turns. Although this surge will not harm the new unit, it increased the registration of the chromium-steel meters under test from a minimum of 100 per cent to a maximum of 430 per cent. It must be emphasized that these changes are laboratory effects as produced by the 13,000-ampere surge and that the crest values of this surge were at least 18,000-amperes. The large range of variation can be accounted for partly by the fact that all the chromium-steel units had not been subjected to the same "knockdown" in manufacture. Also there is some variability between tests because the magnitude of the transient current peaks may have different values dependent upon exactly when the circuit is closed.

The surge-test setup in the laboratory did not simulate correctly the variations in locations and spacings of conductors to be found in the field, but conditions in this setup were the same for both the chromium-steel and the new high-coercive unit. The results should, therefore, have a comparative value and a valid meaning.

Summary

Application of the powerful new aluminum-nickel-cobalt permanent magnet steels to watt-hour meters requires complete redesign of damping units. No mere substitution of the new material is possible. Permanency in the new design is demonstrated. Great savings in weight and space result and the new design can be made much more resistant to transient magnetic disturbances than the common form of chromium steel damping magnet unit which has preceded it.

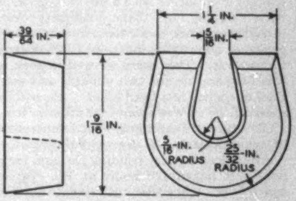


Figure 10. Dimensions of high-coercive damping magnet

Appendix I

Approximate analysis of the new magnets for which permanency data are given is nickel, 20 per cent; aluminum, 12 per cent; cobalt, 5 per cent; carbon, low; iron, remainder. Dimensions of the magnet are given in figure 10. Materials in the alloy were melted under close metallurgical control in a high-frequency induction furnace. Magnets were cast from this furnace into sand molds. After cooling and cleaning, individual magnets were heat treated.

Heat treatment consisted in slowly heating the magnets to 2,000 degrees Fahrenheit and holding at this temperature for a sufficient time to soak the castings thoroughly. Castings were then removed from the furnace and cooled at a predetermined rate in an air blast to 1,250 degrees Fahrenheit. Time required for this cooling ranged from $1^3/_4$ to $2^1/_4$ minutes. They were then placed in a second furnace and held at 1,250 degrees Fahrenheit for 15 minutes, after which they were allowed to cool naturally in air.

After magnetization to saturation, an a-c "knockdown" of not less than 250 ampere turns, mean effective value, was applied around the flux circuit of each magnet with the armature removed. Soft-iron armatures were used separated from the magnet poles 0.120 inch to 0.130 inch. Magnet units were then placed on permanency test.

Production units on single-phase meters have disk gaps averaging 0.100 inch. Permanency figures were, therefore, taken on units with longer gaps and slightly more severe conditions than standard.

Appendix II

Approximate analysis of the chromium-steel magnets for which permanency data are given is carbon, 0.95 per cent; chromium, 3.50 per cent; silicon, 0.25 per cent; iron, remainder. Developed length of the magnet is six inches with a gap of 0.095 inch. After forging to shape, magnets were brought up from room temperature over a period of about 20 minutes to 1,520 degrees Fahrenheit. They were allowed to soak at this temperature for two minutes and were then quenched in a bath of oil. Absorption speed of the oil was about four minutes from 1,520 degrees Fahrenheit to a temperature of approximately 100 degrees Fahrenheit.

After cleaning and grinding the gap, magnets were baked 120 hours at 105 degrees centigrade. They were then surface finished and assembled in brass holding clamps and magnetized to saturation. "Knockdown" by alternating current was applied using at least 180 ampere turns mean effective value for each magnet. A final baking of from four to six hours at 105 degrees centigrade was given.

Magnets in group *B* of figure 8 had both baking steps mentioned above.

Magnets in group *A* of figure 8 had both of these baking steps omitted.

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Discussion

J. P. Larkin (nonmember; Crucible Steel Company of America, Harrison, N. J.): Mr. Green's excellent paper is of great interest to the writer as a representative of one of the licensed manufacturers of Alnico magnets and I would like the opportunity of making a few comments.

As a matter worthy of note in this particular application of Alnico magnets I can say that our company has supplied many thousands of the magnets Mr. Green refers to, over a period of almost three years, to his company. Every magnet shipped has been individually tested magnetically prior to shipment. These magnets are retested before assembling into the meters by a "registration test" and to date no magnets have been returned to us because of low magnetic properties.

Such a record is of interest to the user of magnets because cast magnets of the Alnico type are always furnished by the manufacturer in the heat-treated condition. In the past it has been the practice of many large users of formed or forged magnets to fabricate and heat-treat these magnets in their own plants which always has entailed certain hazards. With the use of Alnico magnets such hazards, of whatever magnitude they may be, are eliminated and the user of these magnets is guaranteed to receive satisfactory and uniform quality because the manufacturer tests each magnet shipped under conditions simulating its actual application in the magnetic circuit.

As stated by Mr. Green, Alnico is melted in high-frequency induction furnaces in relatively small heats. Test bars are poured with each heat and are tested by means of a Leibing model 2 permeameter to establish the B_r and H_c values of each heat. This permeameter and its associated fluxmeter are of quite special design, and used in our laboratory for magnetic standardization work. With this permeameter, H_{max} values up to 3,000 oersteds can be obtained without undue heating, and it is so designed that accurate demagnetization curves can be taken on the finished magnets, for about 90 per cent of the various shapes and sizes which our company is called upon to produce.

By means of permeameter tests and further checks in the customers magnetic circuit, standards can be set for the various magnet designs. Such standards are the basis of production testing of magnets which tests are made either by means of slip coils, search coils, or special testing machines in a circuit with a fluxmeter.

Some questions have arisen regarding the brittleness of Alnico alloys. These alloys are very brittle. Alnico magnets, however, are used generally in tachometers, magnetos, and other moving mechanisms which are subject to impacts and severe reversals of mechanical stress. It is a matter of record that tachometers with rotating Alnico magnets have been in successful use for a period of more than two years when mounted on steam locomotives and aircraft engines. In both cases there is severe impact and vibration, and no mechanical failures have been reported. The same is true for thousands of magnetos used on tractors, stationary engines, and aircraft engines.

For best results Alnico magnets should be designed in the simplest shapes possible. Care should be exercised by the designing engineer to avoid unnecessary constrictions in the sectional area, such as holes or slots for which no allowance has been made. This is detrimental not only from a magnetic standpoint, but also structurally, due to possible weakening of the casting.

Regarding the permanency of Alnico, tests over a period of years indicate that its stability under any given condition is at least as good as the other magnet steels such as cobalt, chromium, or tungsten magnet steel. Its resistance to the demagnetizing effects of temperature and repeated shock or impact is greatly superior to the other magnet steels.

Based on three years of our experience in the manufacture of Alnico magnets under increasingly closer control and inspection, it is safe to say that on production runs of magnets very close uniformity to accepted standards will be maintained. By close and constant co-operation between the research and laboratory staff with the production department better methods of processing are being developed continuously which will result in still higher quality and uniformity than now commercially obtainable.

The variation in either B_r or H_c can be maintained within plus or minus three per cent of the accepted standard when tested in a given type of permeameter. In addition to this range of variation in actual magnetic quality, a range of plus or minus one per cent should be allowed for due to variation in magnet size or weight (particularly on small castings), making the maximum variation in flux to be expected on finished magnets to be in the order of plus or minus four per cent maximum. In discussing variations of this magnitude it should be borne in mind that various standardizing laboratories do not guarantee the accuracy of H_c measurements to be closer than five per cent on high-coercive magnetic alloys.

A. B. Craig (Boston Edison Company, Boston, Mass.): Mr. Green's paper on the design and application of aluminum-nickel-cobalt brake magnets will be read with interest by meter engineers. Research and new developments always make for constructive progress and as such are always welcomed by the utility industry. It is only reasonable that careful and thorough study must be made of the application of this new material, not only in the laboratory but also in the field under service conditions.

Mr. Green has established that under laboratory conditions the permanence of this new magnet material is entirely comparable with that of the existing magnet material. From the data contained in his paper, it appears reasonable to expect that field conditions will confirm this permanence.

Mr. Green has also demonstrated that under laboratory conditions the new magnet material has a greater resistance to the effect of transient 60-cycle magnetic disturbances. As Mr. Green has pointed out in his paper, 60-cycle disturbances of the magnitude required to affect watt-hour meter magnets are rarely encountered in service. No data have been presented to demonstrate that the new material is superior when subjected to a transient with a steep wave front.

A study of the operating experience of utilities discloses that for one company the record of over 100,000 tests shows only 1.0 per cent of all meters tested were over 102 per cent on full load and only 0.3 per cent were found over 104 per cent. Likewise the records indicate that 1.2 per cent of the meters were less than 98 per cent and 0.5 per cent were less than 96 per cent. These results are consistent with the records of a large number of utilities and include weak-

Equivalent Circuits of Transformers and Reactors to Switching Surges

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MEMBER AIEE

THE CALCULATION of switching surges occasioned by circuit-breaker operations requires that transformers, reactors, generators, and other apparatus be replaced by their equivalent circuits. To be of much practical use these equivalent circuits must be simple, as well as reasonably exact. Great accuracy, however, is not required—a 20-per-cent departure from exact values being regarded as tolerable. But the approximate circuit must be very simple; for it is merely one element in a network which may consist of many other elements, all of which enter into the equations which describe the switching surge.

Now a transformer, reactor, or other distributed winding, even in the idealized case, consists of a complicated network of self and mutual inductances, ground and shunt capacitances, series resistances, etc. This circuit is entirely too involved for use in the calculation of switching surges; so it therefore becomes expedient to examine the possibility of a much simpler circuit which will react to switching in essentially the same manner as the apparatus which it replaces. It is, then, the object of this paper to make a theoretical enquiry concerning suitable approximate equivalent circuits of this nature, to compare their behavior with test results, and to suggest how they may be used in switching-surge calculations. The scope of the paper is specifically restricted, however, to transformers and reactors.

Switching surges are calculated on the assumption that the circuit breaker interrupts the current at a 60-cycle "current zero," and the switch operation is simulated mathematically by suddenly applying an equal, but opposite, 60-cycle current which cancels the steady-state value thereafter, and thus, in effect, opens the circuit. Now for all practical purposes this "cancellation current" may be regarded as a current with a linear rate of rise; for during the first few hundred microseconds after a 60-cycle current zero the sinusoid is essentially a straight line. It is to current-surges of this nature that equivalent circuits are to be determined.

Reactors

A reactor, under steady-state conditions, is simply an inductance; but when subjected to a suddenly applied surge of either voltage or current it may exhibit a violent oscillation due to its capacitances to ground and between turns. These capacitances are small, and therefore the natural frequencies of oscillation are high—of the order of 10^5 to 10^6 cycles per second.

The idealized equivalent circuit for a uniformly distributed winding, such as a reactor coil on an iron core, is shown in figure 1, in which the distributed capacitance to ground is represented by *C*, the capacitance between coil sections by *K*, and the inductance by *L* (which includes the effect of the mutual inductance between turns).

Of course in the conventional air-core current-limiting reactor the capacitance to ground, *C*, is not entirely uniformly distributed along the stack, but no great error is committed by assuming it to be so.

On the basis of certain simplifying assumptions regarding the distribution of the mutual inductance between coil sections, the circuit of figure 1 is solved for current surges in appendix I for both a grounded and isolated "neutral" (the end opposite to which the surge is applied). While the complete solution, equation 23, contains an infinite number of harmonics, it is found that only the fundamental is of any practical importance. The line terminal response of a grounded neutral winding to an uniformly rising current surge of the form

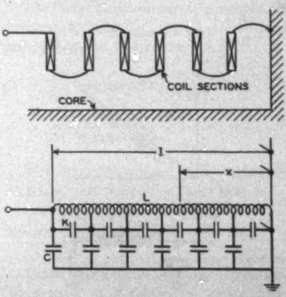

Figure 1. Complete idealized equivalent circuit of the transformer to high-frequency transients

$$i = It \tag{1}$$

is essentially a pure sinusoidal oscillation

$$e = I\frac{L}{3}\left(1 - \cos\frac{\pi^2\alpha t}{2\sqrt{LC(4\alpha^2 + \pi^2)}}\right) \tag{2}$$

This equation contains three parameters: the effective inductance *L* of the winding under high-frequency conditions; the capacitance *C* of the winding to ground; and the characteristic initial distribution factor $\alpha = \sqrt{C/K}$ where *K* is the series

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ening of the magnets from all causes. These figures do not indicate any serious meter troubles.

The use of aluminum-nickel-cobalt brake magnets for watt-hour meters may, if Mr. Green's predictions are justified by field experience, prove another step in the steady development and improvement in watt-hour meters.

Stanley Green: Since first drafts of this paper were prepared, months have gone by during which a continuation of the permanency tests on the new high-coercive magnets has been made. A great many of these magnets have now been on exacting permanency tests for over three years without a single instance being observed to indicate anything contrary to the conclusions of the paper that the new magnet units are perfect as regards permanency with respect to time.

The immunity of the new high-coercive units with respect to other types of disturbances, such as magnetic or mechanical, is a still further insurance of permanency with respect to other factors than time.

The dearth of discussion on the paper may be taken to indicate, I believe, a substantial agreement of readers with respect to the conclusions reached rather than as any lack of interest in the general subject of the application of these new high-coercive magnets to watt-hour meters. As was so kindly mentioned by one of those who discussed the paper, the new magnets are a definite advance in the watt-hour-meter art.

capacitance from end to end of the winding.

It is clear from the form of the equation that after the transient oscillation has died out that the voltage is simply

$$e = I\frac{L}{3} \tag{3}$$

and therefore $L/3$ must represent the total inductance of the winding.

Consider, now, the parallel $L' - C'$ circuit of figure 2 subjected to the current surge of equation 1. Its response voltage is

$$e' = IL'\left(1 - \cos\frac{t}{\sqrt{L'C'}}\right) \tag{4}$$

Comparison of (2) and (4) shows that the simple circuit of figure 2 is equivalent to that of figure 1, under switching surge conditions, if

$$L' = \frac{L}{3} = \text{over-all inductance of the winding} \tag{5}$$

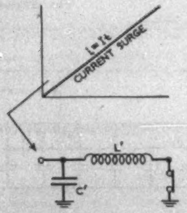


Figure 2. Simplified equivalent circuit of a grounded-neutral transformer to current surges

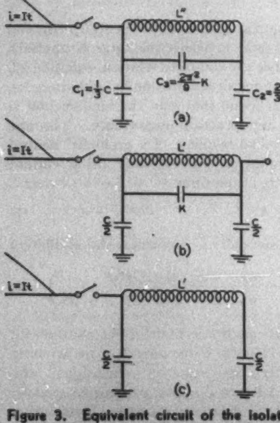


Figure 3. Equivalent circuit of the isolated neutral winding to a current surge

$$C' = \frac{48}{\pi^4}\left(1 + \frac{\pi^2}{4\alpha^2}\right)C = \frac{48}{\pi^4}\left(C + \frac{\pi^2}{4}K\right)$$

$$\cong {}^1/_2\text{ (capacitance to ground)} + \text{(series capacitance)} \tag{6}$$

Thus the uniformly distributed winding with grounded neutral oscillates with a single frequency about its final voltage as an axis; and behaves as though it were a simple $L' - C'$ circuit in which L' is the inductance of the winding, and C' is the sum of half its capacitance to ground and its series capacitance along the stack.

If the neutral is isolated, it is shown in the appendix that the equivalent circuit is that of figure 3*a*. This, however, is an unsymmetrical circuit, the inductance is not directly identifiable, and it is not possible to reduce it to the grounded neutral case by the closing of a switch. The symmetrical circuit of figure 3*b*, in which half the capacitance-to-ground is lumped at each end of the winding, and the inductance is that of the winding, has the same qualitative characteristics as figure 3*a*, and upon grounding the open terminal reduces to the grounded neutral case of figure 2.

It is therefore proposed to adopt figure 3b as the equivalent circuit for a reactor.

The capacitance-to-ground, C, for air-core current-limiting reactors varies, depending upon their size and voltage rating, from 50 to 300 micromicrofarads, but the bulk of them have a capacitance between 100 and 200 micromicrofarads. Placing a reactor in a metal cell will increase the capacitance some 25 per cent. The series capacitance, K, cannot be measured directly, since the turns are continuous, but the calculated values lie between 5 and 25 micromicrofarads; thus may be ignored in comparison with C, and the equivalent circuit reduced to that of figure 3*c*.

A typical oscillogram of the current surge and resulting voltage transient on a grounded neutral reactor is shown in figure 4. This oscillogram was taken with a transient analyzer developed by C. M. Foust and G. W. Dunlap to study circuit transients of this nature by the "current injection method."

Transformer

A transformer differs from a reactor in having two or more windings, and its simplest distributed network would consist of two circuits such as shown in figure 1 superposed. But the solution of the differential equations for two mutually coupled (both magnetically and electrostatically) circuits of this nature is a rather formidable job; and to effect a solution at all necessitates introducing such simplifying assumptions regarding the flux leakages as may seriously invalidate the results. Also, such a solution would hold only if the windings were all on one core leg. For these reasons it is better to build up an equivalent circuit for a transformer by inference, taking advantage of both theory and test in its construction.

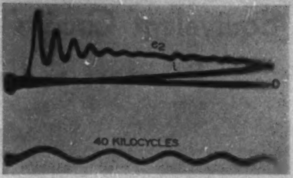


Figure 4. Current-surge and recovery-voltage transient of a reactor (C. M. Foust and G. W. Dunlap)

The circuit of figure 5 appears to fulfill the requirements. It is a double-frequency circuit, just as would be expected from the superpositions of two single-frequency circuits (figures 1 and 2). It reduces to a single-frequency circuit if the secondary winding is grounded throughout its length, or if the two halves of the winding are on different legs of the core. The accessible terminals correspond to the actual terminals of the transformer. In this circuit $C_3 = C_1/2$ is *half* the total capacitance between windings; $C_4 = C_2/2$ is *half* the total capacitance from the secondary to ground (the core). The terminal voltage corresponding to a switching surge, as given in appendix II, is

$$e = LI\,(1 - A\cos\omega t - B\sin\Omega t) \tag{7}$$

in which A and B are fractions whose sum is unity, and L is the leakage reactance between the two windings. Equation 7 is also the solution to figure 5*b*, and this simpler circuit may therefore be regarded as the equivalent circuit of the grounded-neutral transformer with short-circuited secondary.

When the leakage reactance between the two halves of the secondary becomes very large, as when the winding is in series on two legs of the core, it is shown in appendix II that the transformer equivalent circuit reduces to the single-frequency circuit of figure 2, in which L' is then the leakage reactance between primary and secondary windings. Thus it is to be expected that when the windings are all on one core leg, that the voltage transient will have a double frequency, as shown by the oscillograms of figure 6. But when the windings are on two legs,

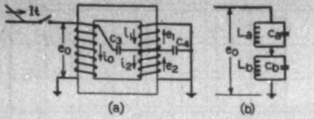


Figure 5. Equivalent circuit of a two-winding transformer to switching surges

Table I

	Bushing Rating (Kilovolts)									
	15	25	37	50	73	92	115	138	161	230
Standard bushing	150	125	100	100	100	140	180	180	180	220
Capacitance bushing							225	225	225	300

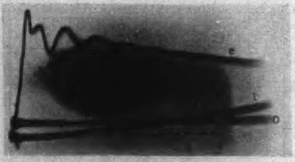


Figure 6. Current-surge and recovery-voltage transient of a transformer—all windings on one leg (C. M. Foust and G. W. Dunlap)

there is essentially only one frequency present, as shown in figure 7. In the former case the oscillatory component was considerably reduced by the shunt resistor used as an oscillograph divider.

While sufficient experimental data are not at hand to permit drawing a blanket conclusion, yet it is believed that *it is permissible to regard figure 2 as the equivalent circuit of a grounded neutral, short-circuited-secondary transformer to switching surges*.

The capacitances C and K and the initial distribution factor α may be accurately calculated from the design sheet.

Average values of the capacitance to ground, C, of single-phase core-type concentric-winding power transformers are given in figure 8. The corresponding values per phase for three-phase transformers are approximately half the values of figure 8. It will be observed that the capacitance increases as the voltage rating decreases, for the reason that the insulation distances are less for the lower voltages. However, as the voltage reaches the lower levels there is very little change in the capacitance, because the insulation distances at these lower voltages are fixed by thermal (oil ducts) and mechanical (cylinders and spacers) considerations, rather than by voltage stresses. Figure 8 also shows that for the higher voltage ratings, the capacitance does not change much with either kilovolt-amperes or kilovolts. These curves show the general trends, but individual transformers may deviate considerably from them.

The α factor for unshielded single-phase core-type, concentric-winding power transformers is given as a band in figure 9. While this factor has a very definite tendency to decrease with an increase in voltage rating, there does not appear to be any correlation with kilovolt-ampere ratings, as evidenced by the crisscrossing of the kilovolt-ampere rating lines inside the band. The band, however, is sufficiently narrow so that no great error is committed by taking a median value. The α factors for three-phase transformers are given in figure 10. In this case there is a distinct difference between those transformers having single-circuit and those having parallel circuit windings, but otherwise the tendency is the same as for the single-phase case. It is to be emphasized that the α factors given in figures 9 and 10 represent the *average* initial distribution throughout the winding, and are *not* an index of the steepness of the initial distribution at the line end corresponding to an abrupt voltage surge. Actual transformers depart from the idealized one analyzed in the appendix, in that their initial distributions do not follow the theoretical α curves near the line end, but exhibit a greater concentration of voltage there; unless this is corrected by shielding.

The series capacitance K is easily estimated from the curves of figures 8, 9, and 10 by the formula

$$K = \frac{C}{\alpha^2} \tag{8}$$

For example, a 30,000-kva 115-kv single-phase transformer has a capacitance to ground, according to figure 8, of $C =$ 4,500 micromicrofarads. A reasonable α factor from figure 9 is $\alpha = 16$. Therefore, the series capacitance would be of the order of

$$K = \frac{4{,}500}{16^2} = 18 \text{ micromicrofarads}$$

thus negligibly small compared to the capacitance to ground C.

The approximate capacitance in micromicrofarads for standard bushings is given in table I.

If the transformer secondary, instead of being short-circuited, is connected to some external impedance, then in the equivalent circuit that impedance is reflected to the primary side by the square of the turn ratio, in the usual way, as shown in figure 11.

EXAMPLE

What is the equivalent circuit of a 6,667-kva 115/23-kv single-phase grounded-neutral transformer connected to a 500-ohm-surge-impedance transmission line on the 115-kv side, and faulted to ground near the 23-kv terminal? The situation is shown in the top diagram of figure 12. The transformer has eight per cent reactance.

The inductance element is simply the leakage inductance of the transformer referred to the 23-kv side and is

$$L' = \frac{10}{2\pi f} \text{ (per cent IX) } \frac{(\text{kv})^2}{(\text{kva})}$$

$$= \frac{10 \times 8 \times 23^2}{377 \times 6{,}667 \times 3} = 0.0056 \text{ henry}$$

The surge impedance of the transmission line, referred to the 23-kv side, is

$$n^2 Z = \left\{\frac{23}{115}\right\}^2 500 = 20 \text{ ohms}$$

From figure 8 the winding capacitance to ground of a 6,667-kva 23-kv transformer would be

$$C = 4{,}900 \text{ micromicrofarads}$$

From figure 9 the α factor would be of the order of $\alpha = 28$ and the series capacitance therefore

$$K = \frac{C}{\alpha^2} = \frac{4{,}900}{28^2} = 6$$

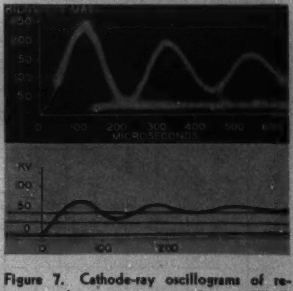


Figure 7. Cathode-ray oscillograms of recovery voltage on power transformers (W. F Skeats)

From the table of bushing capacitances, for a 23-kv bushing

$C_b = 125$ micromicrofarads

Therefore, the equivalent capacitance is

$$C' = \frac{C}{2} + K + C_b = \frac{4{,}900}{2} + 6 + 125 = 2{,}600 \text{ micromicrofarads}$$

The complete equivalent circuit is shown in the bottom diagram of figure 12.

It is clear from the relative values of the capacitances as calculated for this example, that the series capacitance K and the bushing capacitance C_b are of little consequence compared with the ground capacitance C, and may be ignored in comparison therewith.

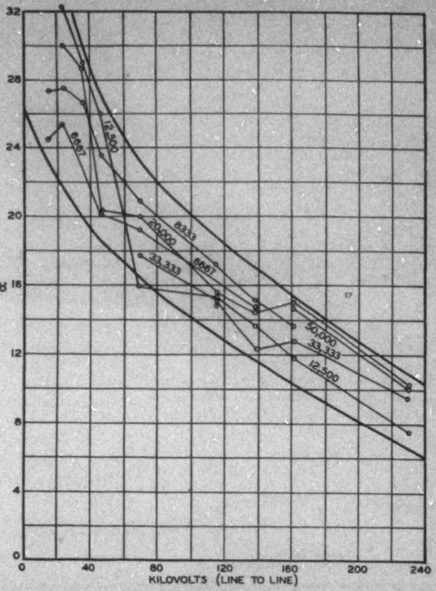


Figure 9. Average α factors for single-phase core-type concentric-winding transformers

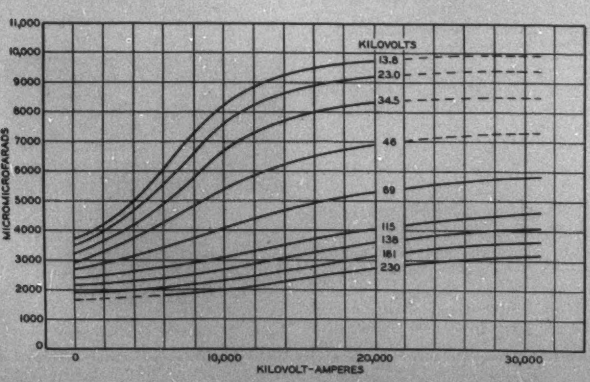
Tests

There are two methods of making switching-surge tests: (1) actual circuit-breaker operation, recording with a cathode-ray oscillograph, and (2) the "current injection" method with a specially designed transient analyzer.

The two oscillograms of figure 7, furnished by W. F. Skeats, show the result of switching-surge tests on large power transformers. In both of these cases the cathode-ray oscillograph divider was a capacitance at the terminal of the transformer, the effect of which was to slow down the natural frequency. It will be noticed that in these oscillograms the oscillations are essentially single frequency, and in the second case it is a pure sinusoid as near as can be told by inspection. The equivalent circuit of figure 2 would therefore be ample for these cases.

The oscillograms of figures 4 and 6 were taken by C. M. Foust and G. W. Dunlap with a modified transient analyzer similar to that developed by K. J. R. Wilkinson[1] for studying switching surges by the "current injection" method. This method consists of injecting current surges into the circuit under test at intervals sufficiently close together so that a steady image is projected onto the screen of the oscilloscope, which image may be photographed for a permanent record. The current surge is a straight line starting at zero and rising at a uniform rate, and therefore simulates a switching-surge current. The oscillogram of figure 6 was taken on the outside winding of a single-phase transformer, the inner winding being short-circuited and grounded. Both windings were entirely on the center core leg. There was, therefore, inductive coupling between the two halves of the inner winding, and in accordance with the theory, the recovery-voltage transient shows the characteristic double-frequency oscillations. Unfortunately, the voltage divider of the transient analyzer was a shunt resistor of such low value that the oscillations were severely reduced, the high-frequency component being nearly critically damped.

Figure 8. Capacitance between windings of power transformers



Appendix I

Grounded-Neutral Single-Winding

The differential equation for the idealized transformer of figure 1, under high-frequency transient conditions, and neglecting the losses, is[2]

$$\frac{\partial^4 e}{\partial x^4} - LK\frac{\partial^4 e}{\partial x^2 \partial t^2} + LC\frac{\partial^2 e}{\partial t^2} = 0 \qquad (9)$$

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1. For all numbered references, see list at end of paper.

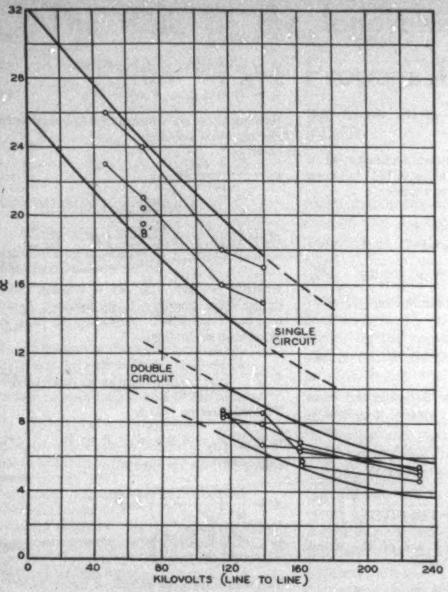

Figure 10. Average α factors for three-phase core-type concentric-winding transformers

A solution, suitable for the present purposes, is

$$e = \Sigma\,(A \sin \lambda x \cdot \sin \omega t + B \sin \lambda x \cdot \cos \omega t + C \cos \lambda x \cdot \sin \omega t + D \cos \lambda x \cdot \cos \omega t) \tag{10}$$

Substitution of (10) in (9) yields the following relationship between the space wave length λ and the time wave length ω,

$$\omega = \frac{\lambda^2}{\sqrt{L(C + K\lambda^2)}} \tag{11}$$

At the grounded neutral of the transformer, $x = 0$, the voltage is zero for all time, and (10) then gives

$$0 = \Sigma(C \sin \omega t + D \cos \omega t), \text{ or} \\ C = D = 0 \tag{12}$$

At the line end of the winding, $x = 1$, the voltage is initially ($t = 0$) zero, since a finite current cannot instantaneously build up a voltage across a capacitance network. Therefore by (10)

$$0 = \Sigma B \sin \lambda \cdot \cos \omega t, \text{ or } B = 0 \tag{13}$$

The voltage equation thus reduces to

$$e = \Sigma A \sin \lambda x \cdot \sin \omega t \tag{14}$$

The total current flowing through the transformer is[3]

$$i = C\int \frac{\partial e}{\partial t}\,dx = -C\sum \frac{\omega}{\lambda} A \cos \lambda x \cdot \cos \omega t + I(t) \tag{15}$$

in which $I(t)$ is an integration constant with respect to x, and is therefore a possible function of t. At the line end, $x = 1$, the current is the applied current I, so that

$$I = I(t) - C\sum \frac{\omega}{\lambda} A \cos \lambda \cdot \cos \omega t \tag{16}$$

from which it is clear that

$$I(t) = I \text{ and } \lambda = \frac{s\pi}{2};\; s = 1, 3, 5, \ldots \tag{17}$$

That part of the through current confined to the inductance is

$$i_L = i - i_k = i - K\frac{\partial^2 e}{\partial x\,\partial t} = I - \sum \frac{\omega}{\lambda}(C + \lambda^2 K)\,A \cos \lambda x \cdot \cos \omega t \tag{18}$$

Initially this current must be zero, since time is required to build up a current in an inductive circuit. Thus at $t = 0$

$$0 = I - \sum \frac{\omega}{\lambda}(C + \lambda^2 K)\,A \cos \lambda x \tag{19}$$

Expressing I as a cosine series on the wave length λ,

$$\frac{4}{\pi} I \sum \frac{\sin \frac{s\pi}{2}}{s} \cos \frac{s\pi x}{2} = \sum \frac{\omega}{\lambda}(C + \lambda^2 K)\,A \cos \lambda x \tag{20}$$

Therefore, substituting for λ from (17), the A coefficients are found to be

$$A_s = I\sqrt{\frac{L}{C}}\,\frac{16\,\alpha \sin \frac{s\pi}{2}}{s^2\pi^2\sqrt{4\,\alpha^2 + s^2\pi^2}} \tag{21}$$

where

$$\alpha = \sqrt{C/K} \tag{22}$$

is the characteristic initial distribution factor[3] of the transformer.

The voltage equation now becomes, explicitly:

$$e = I\sqrt{\frac{L}{C}} \sum_{1,3,5}^{\infty} {}_s \frac{16\,\alpha \sin \frac{s\pi}{2}}{s^2\pi^2\sqrt{4\,\alpha^2 + s^2\pi^2}} \times \sin \frac{s\pi x}{2} \sin \frac{s^2\pi^2\alpha t}{2\sqrt{LC(4\,\alpha^2 + s^2\pi^2)}} \tag{23}$$

If the applied current surge, instead of being a "unit function," rises linearly at a uniform rate $i = It$, then the application of Duhamel's theorem to (23) gives

$$e = IL\sum_{1,3,\ldots}^{\infty} \frac{32}{s^4\pi^4} \sin \frac{s\pi}{2} \sin \frac{s\pi x}{2} \times \left[1 - \cos \frac{s^2\pi^2\alpha t}{2\sqrt{LC\,(4\,\alpha^2 + s^2\pi^2)}}\right] \tag{24}$$

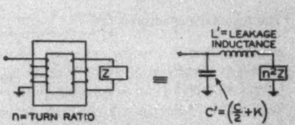

Figure 11. Equivalent circuit with external impedance in secondary circuit

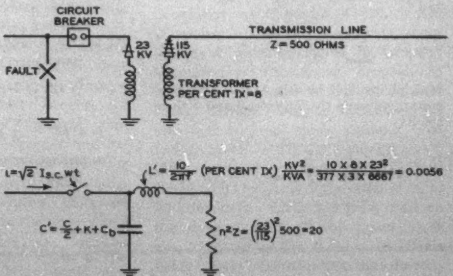

Figure 12. Example illustrating use of the simplified equivalent circuit of a transformer

Due to the presence of s^4 in the denominator of this equation it is clear that only the fundamental is of importance. For example, the next harmonic—the third—is only $1/3^4 = 0.012$ of the fundamental. Therefore, for all practical purposes

$$e \cong IL \frac{32}{\pi^4} \sin \frac{\pi x}{2} \times \left[1 - \cos \frac{\pi^2 \alpha t}{2\sqrt{LC(4\alpha^2 + \pi^2)}}\right] \tag{25}$$

and at the line terminal of the transformer this becomes

$$e = I\frac{L}{3}\left[1 - \cos \frac{\pi^2 \alpha t}{2\sqrt{LC(4\alpha^2 + \pi^2)}}\right] \tag{26}$$

Single-Phase Isolated Neutral

When the neutral is isolated, there must be a continual increase in voltage for an applied unit function current, for charge is indefinitely accumulating on the capacitance to ground. Assume a solution of the form

$$e = Et + \Sigma D \cos \lambda x \cdot \sin \omega t \tag{27}$$

substitution of which in the differential equation 9 again yields (11) as the relationship between the space and time harmonics. The total current flowing along the stack is

$$i = C \int \frac{\partial e}{\partial t} dx = I(t) + CEx + C\sum D \frac{\omega}{\lambda} \sin \lambda x \cdot \cos \omega t \tag{28}$$

The current flowing in the inductance is

$$i_L = i - i_k = i - K \frac{\partial^2 e}{\partial x \partial t} = I(t) + CEx + \sum D\frac{\omega}{\lambda}(C + K\lambda^2) \sin \lambda x \cdot \cos \omega t \tag{29}$$

The boundary conditions are:

$$\left.\begin{aligned} e &= 0 \text{ at } t = 0 \\ i &= 0 \text{ at } x = 0 \\ i &= I \text{ at } x = 1 \\ i_L &= 0 \text{ at } t = 0 \end{aligned}\right\} \tag{30}$$

These are satisfied by putting

$$CE = I, \quad I(t) = 0, \quad \lambda = s\pi \tag{31}$$

and

$$0 = Ix + \sum D_s \frac{\omega_s}{\lambda_s}(C + K\lambda_s^2) \sin \lambda_s x \tag{32}$$

Multiplying (32) by $(\sin \lambda x \cdot dx)$ and integrating between the limits of 0 and 1 there results

$$D_s = \frac{2I}{s^2\pi^2}\sqrt{\frac{L}{C + Ks^2\pi^2}} \cos s\pi \tag{33}$$

The voltage equation now becomes

$$e = I\frac{t}{C} + 2I\sum_1^\infty{}_s \sqrt{\frac{L}{C + Ks^2\pi^2}} \times \frac{\cos s\pi}{s^2\pi^2} \cos s\pi x \cdot \sin \omega_s t \tag{34}$$

If the applied current increases at a uniform rate, an integration of (34) between the limits $t = 0$ and $t = t$ gives

$$e = I\frac{t^2}{2C} + 2IL\sum_1^\infty \frac{\cos s\pi}{s^4\pi^4} \times (1 - \cos \omega_s t) \cos s\pi x \tag{35}$$

The fundamental at the line end $(x = 1)$ is

$$e_1 = I\left[\frac{t^2}{2C} + \frac{2}{\pi^4} L(1 - \cos \omega_1 t)\right] \tag{36}$$

The circuit of figure 3*a* subjected to a uniformly rising current surge responds as

$$e'' = I\left[\frac{t^2}{2(C_1 + C_2)} + \left(\frac{C_2}{C_1 + C_2}\right)^2 L'' \times \left(1 - \cos t\sqrt{\frac{C_1 + C_2}{L''(C_1C_2 + C_1C_3 + C_2C_3)}}\right)\right] \tag{37}$$

Equations 36 and 37 are of the same form and become identical if

$$C_1 = \frac{1}{3}C, \quad C_2 = \frac{2}{3}C, \quad L'' = \frac{9}{2\pi^4}L, \quad C_3 = \frac{2\pi^2}{9}K \tag{38}$$

and therefore suggests figure 3*a* as the appropriate equivalent circuit.

Appendix II

The canonical equations for the three-winding transformer of figure 5*a* are[3]:

$$e_1 - n_1e_0 = Z_{11}i_1 + Z_{12}i_2 \tag{39}$$

$$e_2 - n_2e_0 = Z_{21}i_1 + Z_{22}i_2 \tag{40}$$

$$-i_0 = n_1i_1 + n_2i_2 \tag{41}$$

in which, since windings number 1 and number 2 are alike and symmetrical,

$n_1 = n_2 = n =$ (turns of number 1 or number 2)/(turns of number 0)

$Z_{11} = Z_{22} = n^2Z_{0-1} = n^2pL' =$ leakage impedance, number 0 to number 1

$$Z_{12} = \frac{n^2}{2}(Z_{0-1} + Z_{0-2} - Z_{1-2}) = n^2pL' - \frac{n^2}{2}pL''$$

= leakage impedance number 1 to number 2

The constraints of the circuit are:

$$e_1 + e_2 = 0 \tag{42}$$

$$i_1 = i_2 + C_4pe_1 - C_3p(e_0 - e_2) \tag{43}$$

$$i = It = C_3p(e_0 - e_2) + i_0 \tag{44}$$

Solving these six simultaneous equations for the terminal voltage:

$$e_0 = \frac{C_4 + C_3}{C_3C_4} \times \frac{[p^2 + 4/n^2L''(C_3 + C_4)]I}{p^4 + \left(\frac{4}{n^2L''C_4} + \frac{C_3 + C_4}{LC_3C_4}\right)p^2 + \frac{4}{n^2L''C_3C_4}} \tag{45}$$

where $L = (L' - L''/4) =$ leakage impedance from number 0 to number 1 and number 2 in series. Equation 45 may be expressed in the form

$$e_0 = \frac{C_4 + C_3}{C_3C_4} \frac{p^2 + w^2}{(p^2 + \omega^2)(p^2 + \Omega^2)} I \tag{46}$$

The solution to (46) is

$$e_0 = LI(1 - A \cos \omega t - B \sin \Omega t) \tag{47}$$

where

$$A = \frac{\Omega^2}{w^2}\left(\frac{\omega^2 - w^2}{\omega^2 - \Omega^2}\right) \text{ and } B = \frac{\omega^2}{w^2}\left(\frac{\Omega^2 - w^2}{\Omega^2 - \omega^2}\right) \tag{48}$$

The solution to the circuit of figure 5*b* is

$$e = (L_a + L_b)I\left(1 - \frac{L_a}{L_a + L_b} \times \cos \frac{t}{\sqrt{L_aC_a}} - \frac{L_b}{L_a + L_b} \cos \frac{t}{\sqrt{L_bC_b}}\right) \tag{49}$$

Thus figure 5*b* is equivalent to figure 5*a* if

$$L_a = AL; \quad L_b = BL; \quad C_a = \frac{1}{\omega^2AL}; \quad C_b = \frac{1}{\Omega^2BL} \tag{50}$$

If the leakage inductance L'' between the two halves of the secondary winding is very large $(L'' \rightarrow \infty)$, as is the case when the windings on the two legs of the core are in series, then the terms of (45) containing L'' drop out and its solution becomes the single-frequency transient

$$e_0 = LI\left(1 - \cos\sqrt{\frac{C_3 + C_4}{LC_3C_4}}\, t\right) \tag{51}$$

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1. Recurrent-Surge Oscillographs and Their Application to Short-Time Transient Phenomena, K. J. R. Wilkinson. Institution of Electrical Engineers, November 1938.

2. Traveling Waves on Transmission System (a book), L. V. Bewley. John Wiley and Sons, chapter 13.

3. Tensor Algebra in Transformer Circuits, L. V. Bewley. Electrical Engineering, November 1936.

The Role of the Ionosphere in Radio Wave Propagation

J. H. DELLINGER
NONMEMBER AIEE

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I. Introduction

When Marconi electrified the world in 1901 by sending radio signals across the Atlantic Ocean, he incidentally proved that the upper atmosphere is electrified. Diffraction was insufficient to explain the bending of the electromagnetic waves around the 30 degrees of the earth's curved surface. The waves could not penetrate the earth. So there was only one way they could go the incredible distance, and that was by reflection from one or more conducting strata in the atmosphere. So reasoned Professor A. E. Kennelly, and he published[1] the idea a few months after Marconi's demonstration. Oliver Heaviside reached the same conclusion and published[2] it at nearly the same time; his paper however mentioned only a single layer. This postulated layer was known for a number of years as the Kennelly-Heaviside layer, and the entire ionized region in the upper atmosphere which affects the transmission of radio waves is now called the ionosphere. Radio waves transmitted by means of it are called sky waves, in contradistinction to the ground waves, those which are propagated along the earth's surface.

While it might at first be astonishing that the extremely rare upper atmosphere could contain enough material to affect the passage of radio waves, yet the very thinness of the air is what permits this to happen. At a height of 100 kilometers (62 miles) above the earth's surface, for example, the air pressure is probably much less than a millionth of what it is at the earth's surface, or the equivalent of a vacuum in an electric-discharge vacuum tube. The air particles are separated so far from one another that collisions are far less frequent than in the lower atmosphere, and when an atom is ionized by solar radiation it remains ionized for a considerable time. Therefore at any given time a large proportion of the air particles are in an ionized condition. When a radio wave passes through such ionized air the electric force of the wave accelerates the ions, which take on a certain amount of motion at the wave frequency, this accelerated motion in turn giving rise to radiation. There is thus an interchange of energy between the ionized air particles and the radio waves, with a net effect of reflection or refraction of the waves.

It has been found from radio experiments that this ionized condition does not increase uniformly as the air pressure decreases with altitude. Because of varying distribution of chemical composition of the air with height, and because of the different gases' differing capability of absorption of solar radiation of different frequencies, there are certain strata or layers in the air in which a maximum of ionization exists, that is, the ionization is greater than it is either above or below the layer.

The ionization of the ionosphere layers is principally due to ultraviolet radiation from the sun. The detailed processes by which the ionization is produced and maintained at any given level, are obscured by the almost complete lack of precise knowledge of the composition, state of dissociation, and temperature at those levels. The ionization produced in the daytime is carried over into the night by chemical, electrical, or other reactions which are at present unknown. Some speculation has appeared in print on some of the details, but that is outside the scope of this paper, which is essentially a presentation of the known facts. These facts are fairly complicated, and it is noteworthy that while some of them have been explained by some of the speculative theory, such theory has in each case been developed to fit the facts after the facts had been discovered.

IONOSPHERE STRUCTURE

Since the distribution of energy in the spectrum of radiation from the sun, and likewise possibly the chemical composition and temperature of the air at different heights, vary at different times of the day and year, the ionized layers in the atmosphere do not remain always at the same height but vary diurnally, seasonally, and otherwise, in both height and ionization. There may be a considerable number of such layers at a given time. Of these, two are permanent, and two others are semi-permanent. The two permanent ones are called the *E* and *F* layers. The *E* layer is at a height of 90 to 140 kilometers at different times, usually about 110 kilometers. The term *F*-layer is ordinarily reserved for the other layer as it exists at night; in the daytime during most of the year it divides into two layers which are called the F_1 and F_2. The night *F* layer is at a height of 180 to 350 or more kilometers. The F_1 layer exists in the daytime (except in winter), at a height of 130 to 250 kilometers. The F_2 layer exists every day, at a height of 250 to 350 or more kilometers in the summer, dropping to about 150 kilometers in the winter day. (The "virtual" heights, defined later, are higher than these values.) The fourth layer, which is semipermanent, is the *D* layer; it exists only in the daytime and its height is of the order of 50 to 90 kilometers. Little has been done on the determination of the quantitative characteristics of the *D* layer, its effects being largely inferred rather than directly

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[1] "On the Elevation of the Electrically Conducting Strata of the Earth's Atmosphere," A. E. Kennelly, *Electrical World and Engineer*, volume 39, March 15, 1902, page 473.

[2] "Telegraphy," Oliver Heaviside, Encyclopedia Britannica, tenth edition, volume 33, December 19, 1902, page 215.

observed. Existing knowledge covers mainly the E, F, F_1, and F_2 layers.[2a]

The structure of the ionosphere may be visualized in an elementary way from figure 1, which is for a typical summer daytime condition, the F_1 and F_2 layers both being present as well as the E. This is drawn to scale, so the angles of reflection of radio waves from the layers may be estimated correctly. The three layers are shown as mere thin lines, for simplicity. The layers have in fact a certain thickness, and the density of ionization varies somewhat in this thickness. At the right of the diagram is a rough illustration of a possible distribution of ionization density with height.

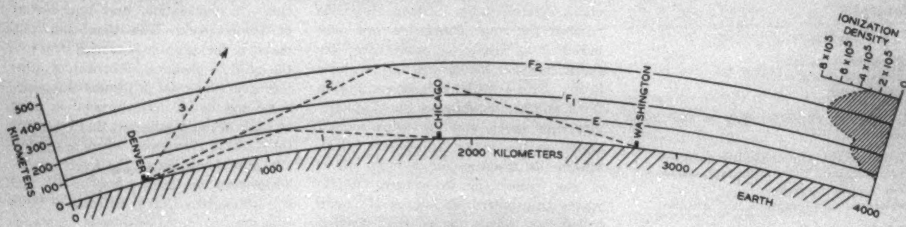


Figure 1. The principal layers of the ionosphere, drawn to scale for a particular time of day and year

Dotted lines indicate two of many possible paths of radio waves from a transmitter to a receiver as transmitted by reflection from the ionosphere layers. This picture, simple as it is, does in fact represent the basic mechanism of radio-wave transmission over long distances. When we consider the variations of ionization and height of the layers with time, and the effects of the ionization upon the received intensity and the limits of transmissible frequency at any particular time, the picture loses its simplicity. The purpose of the present paper is to outline the principal known facts and implications of this complicated situation. We shall see that the phenomena of long-distance radio transmission may be completely explained by the ionosphere.

Ionosphere Characteristics

There are three principal ionosphere characteristics which determine radio transmission. These are the height, the ionization density, and the energy absorption capability of each of the ionosphere layers. Since each layer has a certain thickness it is necessary to define the sense in which the term height is used. A ray or wave train starts to bend toward the ground immediately upon entering the layer, as illustrated in figure 2, and follows a curved path in the layer until it emerges at the same vertical angle at which it entered. It has been shown[3] that the time of transmission along the actual path BCD in the ionized layer is the same as would be required for transmission along the path BED if there were no ionized particles present. The height h, from the ground to E, the intersection of the two projected straight parts of the path, is called the virtual height of the layer. This is the important quantity in all measurements and applications.

The virtual height of a layer is measured by transmitting a radio signal from A, and receiving at F both the signal transmitted along the ground and the echo, or signal reflected by the ionosphere, and measuring the difference in time of arrival of the two. The signal is a special, very short pulse in order that the two may be separated in an oscillograph, as the time differences are mere thousandths of a second. The difference between the distance $(AE + EF)$ and AF is found by multiplying the measured time difference by the velocity of light. From this and the known distance AF, the virtual height h is calculated. It is usually convenient to make AF zero, that is, to transmit the signal vertically upward and receive it at the same place (and the term "virtual height," rigorously defined, is for this case).

The effectiveness of the ions in reflecting the waves back to earth depends on the number of ions present in a unit of volume, that is, the ionization density. It requires a greater density of ionization to reflect the waves back to earth, the higher the frequency. It has been shown that, for electron ionization, the relation[4] (for the ordinary ray) is

$$N = 0.0124 f^2 \qquad (1)$$

where N is the number of electrons per cubic centimeter and f is the highest frequency, in kilocycles per second, at which waves sent vertically upward are reflected back to earth. Waves of all frequencies higher than this pass on through the ionized layer. This frequency is called the critical frequency, and measurement of it is, with the equation just given, a means of measuring the maximum ionization density in an ionized layer.

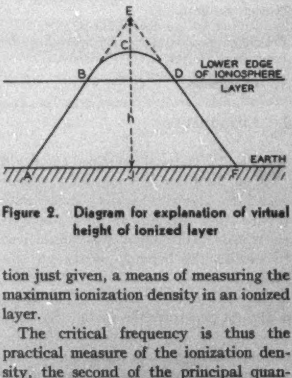


Figure 2. Diagram for explanation of virtual height of ionized layer

The critical frequency is thus the practical measure of the ionization density, the second of the principal quantities determining the role of the ionosphere in radio transmission. The way the critical frequency is measured is to determine the virtual height of the layer by the method mentioned above, using vertical or nearly vertical transmission (that is, with the transmitter and receiver not far apart), and keep increasing the frequency until signals are no longer received back from the layer. The highest frequency at which signals are received back from the layer is the critical frequency of that layer. (For some purposes this definition is not exact; see discussion of "sporadic E" in section IV.) The results of such a measurement are illustrated in figure 3. Starting at a frequency below 2,000 kilocycles per second, the virtual height is found to be about 110 kilometers, and remains at about this height until about 3,000 kilocycles per second. The critical frequency of the E layer at the time of this measurement is thus 3,000 kilocycles per second. At this frequency the waves penetrate the E layer and go on up to a higher layer, the F_2. The F_2 layer has a greater ionization density and so it reflects back waves of frequency greater than 3,000 kilocycles per second. It is not until frequencies greater than 12,000 kilocycles per second are used that the F_2 layer fails to reflect them, in the case illustrated.

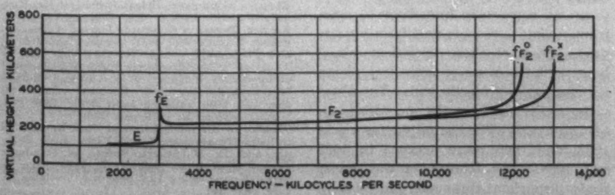
[2a] The D, E, and F layers were first identified by E. V. Appleton (Papers of the URSI General Assembly, Washington, 1927, volume 1, part 1, page 2). The F_1 and F_2 layers were first identified by J. P. Schafer and W. M. Goodall (*Nature*, volume 131, 1933, page 804) and S. S. Kirby, L. V. Berkner, and D. M. Stuart (IRE *Proceedings*, volume 21, 1933, page 757). The D layer was first shown to serve as a reflecting layer by N. Smith and S. S. Kirby (*Physical Review*, volume 51, 1937, page 890).

[3] Page 571 of article, "A Test of the Existence of the Conducting Layer," G. Breit and M. A. Tuve, *Physical Review*, volume 28, 1926, page 554.

[4] Relation evolved through the work of Eccles (1912); Larmor (1924); Breit and Tuve (1926); Appleton (1931); Gilliland, Kenrick, and Norton (1931); and given as equation 5a of "Studies of the Ionosphere and Their Application to Radio Transmission," S. S. Kirby, L. V. Berkner, D. M. Stuart, Bureau of Standards *Journal of Research*, volume 12, 1934, page 15 (research paper 632). A summary of the scientific aspects of the ionosphere is given in "The Physics of the Ionosphere," H. R. Mimno, *Reviews of Modern Physics*, volume 9, 1937, page 1; this article also presents a valuable bibliography, comprising 309 references (the literature is so extensive that even this list is far from complete).

Near the critical frequency the waves are excessively retarded in the ionized layer, which accounts for the abnormal rise of the curve at the critical frequency. At the right of the curve appear two critical frequencies for the F_2 layer. This is an indication of double refraction of the waves due to the earth's magnetic field, two components of different polarization being produced. One is called the ordinary ray and the other the extraordinary ray. The symbols o and x are used for these, respectively. The critical frequency of a layer n is represented by the symbol f_n, and to such symbol the o or x is added as a superscript. Thus the critical frequencies of the F_2 layer for the ordinary and extraordinary rays are indicated by the respective symbols, $f_{F_2}^{o}$ and $f_{F_2}^{x}$. In the case of the E layer, usually the ordinary ray predominates and the extraordinary ray is so weak it does not affect radio reception.

Figure 3. Relation between observed virtual height and frequency of radio waves



Automatic recording equipment is used by the National Bureau of Standards and a few other laboratories to record the virtual heights and critical frequencies of the ionosphere layers. A sample record is shown in figure 4. In this case (afternoon in May 1933) the E-layer critical frequency was 2,900 kilocycles per second and the F_1-layer critical frequency was 3,800 kilocycles per second. The dark curved line in the upper right corner of the figure of the same shape as the line below it, is a multiple reflection, that is, the wave was not only reflected back from the F_2 layer, causing the lower line, but was then reflected back up from the earth's surface and down again a second time from the F_2 layer.

Measurements of the type just described are usually made at vertical incidence, that is, the waves are transmitted straight up to the ionosphere and received at a place not far from the transmitter. Strange as it may seem, such measurements tell us a great deal about long-distance radio transmission. Thus, from the results of such measurements can be calculated the upper limit of frequency usable over any given distance. A simple relation for reflection from a sharply defined layer follows from consideration of its dielectric constant and index of refraction. To a first approximation,[5]

$$f_m = f_c \sec \phi = f_c/\cos \phi \qquad (2)$$

where f_m is the maximum usable frequency over any distance, f_c is the critical frequency measured as above described at vertical incidence, and ϕ is the angle of incidence of the waves at the ionosphere, that is, the angle between the wave's line of travel a and the vertical line giving the virtual height h in figure 5. This is only a first approximation, as we shall see later, but it is close enough to permit estimating certain important effects and results. From figure 5,

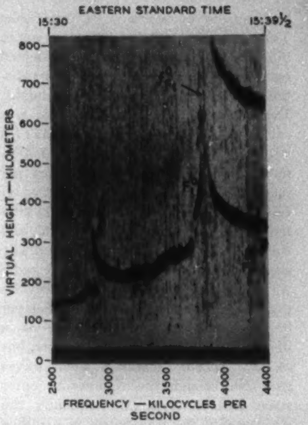


Figure 4. Example of frequency-height record as recorded by automatic multifrequency recorder of ionosphere echoes

May 8, 1933

$\sec \phi = a/h$, h being the virtual height of the ionized layer. Also,

$$a = \sqrt{\frac{d^2}{4} + h^2}$$

d being the horizontal distance of transmission. Therefore,

$$f_m = f_c\sqrt{\frac{d^2}{4h^2} + 1} \qquad (3)$$

This is the approximate relation between the maximum usable frequency at a distance d between transmitter and receiver, and the two important characteristics of the ionosphere layer, the virtual height h and critical frequency f_c.

SKIP DISTANCE

An interesting consequence of this relation is: the distance at which a given frequency is the maximum usable is also the minimum distance over which that frequency is receivable, that is, there is a zone around the transmitter in which the frequency is not receivable but outside of which it is receivable. Thus figure 6 shows the calculated upper limit of frequency of waves reflected back by the ionosphere for various distances, for a particular time (midnight, December 1937, *F* layer). This was calculated by the simple formula (3) with the virtual height $h = 310$ kilometers and $f_c = 4{,}180$ kilocycles per second. The maximum frequency receivable at a distance of, say, 1,200 kilometers is 8,300 kilocycles per second, and this is higher than that receivable at any shorter distance. This means that radio waves of a frequency of 8,300 kilocycles per second are reflected by the *F* layer of the ionosphere and receivable at a distance of 1,200 kilometers or more, but at any shorter distance such waves pass on through the *F* layer to outer space and are lost. Consequently the zone around the transmitter of a radius of 1,200 kilometers is a skipped zone for the frequency of 8,300 kilocycles per second, and the distance of 1,200 kilometers is called the skip distance for that frequency at that time. There is good reception beyond the skip distance and none within it. This is subject to the qualification that there is a short distance close to the station in which reception by the ground wave is possible; this is of no interest in long-distance reception and is outside the scope of this paper. There is also some reception, usually weak and unsatisfactory, within the skipped zone due to scattered reflection of waves from irregular ionized patches in the ionosphere (see section IV hereinafter).

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[5] Relation following directly from Snell's law of refraction and Eccles-Larmor equations for index of refraction in an ionized medium. Derived by my colleagues in National Bureau of Standards in 1934; published in "Multifrequency Ionosphere Recording and Its Significance," by T. R. Gilliland, National Bureau of Standards *Journal of Research*, volume 14, 1935, page 283 (research paper 768); in document "Study of Question 7 Proposed for the Fourth Meeting of the C.C.I.R., Report Submitted by U.S.A.," 1936; and elsewhere, for example, in "Maximum Usable Frequencies for Radio Sky-Wave Transmission, 1933 to 1937," by T. R. Gilliland, S. S. Kirby, N. Smith, S. E. Reymer, National Bureau of Standards *Journal of Research*, volume 20, 1938, page 627 (research paper 1,096).

The reality of the skip distance is quite striking. It frequently happens that, in order to get radio messages through on a certain high frequency over a short distance, two stations not far apart communicate with one another by relaying their messages through a third station a great distance from both. For example, two stations in Pennsylvania 100 kilometers apart may be unable to send messages directly to each other on 15,000 kilocycles per second but both may easily communicate with a station in South America and relay messages through it to each other.

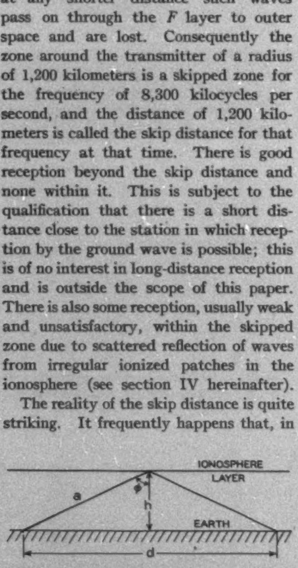

Figure 5. Simplified geometry of angle of incidence of radio waves on ionosphere layer

II. Regular Characteristics of the Ionosphere

Since the upper limits of frequency usable for radio transmission over a given distance depend directly upon the virtual heights and critical frequencies of the layers of the ionosphere, and since these are constantly varying with time of day, season, and other factors, it is particularly important to have definite data on the variations of these two ionosphere characteristics. Radio transmission conditions in general follow the critical frequencies; for example, when the critical frequencies are high the maximum usable frequencies and the best frequencies for radio communication are also high. In view of the known relations between radio transmission and ionosphere data, the facts of radio transmission can indeed be summarized in far more compact form in terms of ionosphere data than in terms of direct radio data.

A survey of the factual data of the ionosphere is in some respects like a survey of weather conditions. Like the predominant roles played in weather phenomena by atmospheric pressure, temperature, and humidity, we have the predominant roles played in ionosphere phenomena by the ionization, the virtual height, and the absorption. Our task is to learn the characteristic variations of these factors. While the two realms, weather and ionosphere, have this similarity, they are, so far as we know, independent of each other. Weather is local; the ionosphere phenomena are worldwide. Weather is due to happenings in the troposphere, extending about ten kilometers above the earth's surface, while the ionosphere phenomena occur at heights many times this. The seasonal effects in the ionosphere are synchronous with the sun's position, not lagging a month or two as do the seasons of weather. Ionosphere phenomena exhibit a greater regularity than weather phenomena and are in some respects better understood.

A large body of facts regarding the virtual heights and critical frequencies of the ionosphere layers is now available. Much less is known about the absorption. All three vary from hour to hour, from season to season, and from year to year. Each of these variations would be expected because of their dependence upon radiation from the sun. The ultraviolet radiations from the sun vary in an 11-year cycle. The last minimum was in 1933, and there were maxima in 1927 and 1938. The ionosphere was under study throughout this cycle, and we have consistent data particularly for the last six years. The present is a good time to summarize the facts of the ionosphere, for it is only now that we have come into comprehensive possession of such facts throughout the entire significant period of half a solar cycle.

The only place where the ionosphere is known to have been continuously under observation for this period is the National Bureau of Standards at Washington. The measuring technique[6] involves oscillographic observation of radio echoes of a sharp pulse. Similar work has been done from time to time by numerous observers and laboratories, and continuous observations are now in progress in many countries. Knowledge of the behavior of the ionosphere is coming to be so important in the operation of radio services that the National Bureau of Standards broadcasts information on the ionosphere characteristics and vagaries from its radio station WWV one day each week. These regular broadcasts were begun in 1937. It may be necessary in the future to have such service daily from a number of places, like the weather-forecasting service.

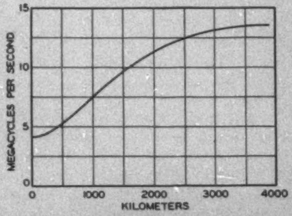

Figure 6. Relation between limit of frequency receivable and distance of transmission, calculated by simplified formula for a particular time (midnight, December 1937, F layer)

Virtual Heights and Critical Frequencies

A satisfactory way in which to present and use the data on ionosphere layer heights and critical frequencies is by means of graphs of monthly averages of these quantities as a function of time of day. The monthly average is significant because the variations from day to day are small, usually less than 15 per cent, except for disturbed days, which constitute a separate subject, treated in section IV. Typical examples of the monthly average graph are given in figure 7, showing summer and winter conditions. Similar curves have been published[7] by the National Bureau of Standards for every month from May 1933 to the present, and continue to be published in the *Proceedings* of the Institute of Radio Engineers each month. Such data are also published[8] in tabular form every quarter.

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[6] "A Test of the Existence of the Conducting Layer," G. Breit and M. A. Tuve, *Physical Review*, volume 28, 1926, page 554.
"Preliminary Note on an Automatic Recorder Giving a Continuous Height Record of the Kennelly-Heaviside Layer," T. R. Gilliland and G. W. Kenrick, Bureau of Standards *Journal of Research*, volume 7, page 783, 1931 (research paper 373); IRE *Proceedings*, volume 20, 1932, page 540.
"Note on a Multifrequency Automatic Recorder of Ionosphere Heights," T. R. Gilliland, Bureau of Standards *Journal of Research*, volume 11, page 561, 1933 (research paper 608); IRE *Proceedings*, volume 22, 1934, page 236.
"Studies of the Ionosphere and Their Application to Radio Transmission," S. S. Kirby, L. V. Berkner, and D. M. Stuart, Bureau of Standards *Journal of Research*, volume 12, 1934, page 15 (research paper 632); IRE *Proceedings*, volume 22, 1934, page 481.

The virtual heights shown in these graphs are the heights for the lowest frequencies used in the determinations. There is a slight variation of height with frequency, as suggested in figure 3, and as discussed in section III hereinafter, but the variation is small and can be neglected for many purposes. The vertical dashed lines on the graphs are for the times of sunrise and sunset at the ground, not the earlier sunrise time and later sunset time at those heights in the atmosphere where the ionosphere layers are located. While this is surprising at first sight, the ground times of sunrise and sunset are the logical ones to consider, because the sunlight arriving tangentially to the earth's surface cannot reach any atmospheric level above the dark hemisphere without having first traveled down through that and lower levels above the lighted hemisphere, and the ionizing radiation would be largely absorbed in those lower levels. Doubtless some of the ionizing radiation does reach the ionosphere somewhat before ground sunrise and after ground sunset, but it is by scattering, diffusion, or other special process.

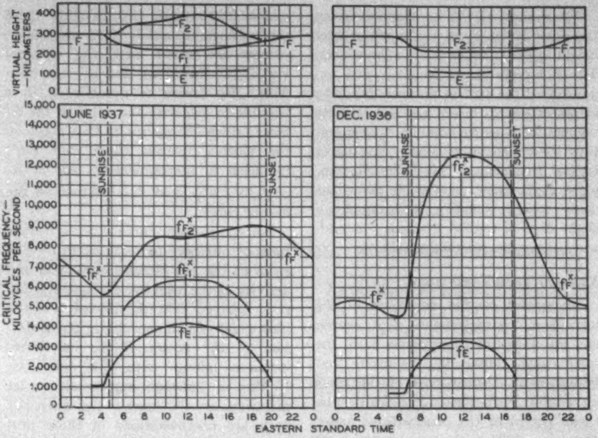

Figure 7. Typical summer and winter monthly averages of the diurnal variation of virtual heights and critical frequencies

The abscissas in figure 7 are time of day (Eastern standard time), on a 24-hour basis, for example, 0 = midnight, 14 = 2 p.m., etc. The following symbols are used:

f_E = critical frequency of the E layer. This is the critical frequency of the ordinary ray unless otherwise specified. When it is desired to specifically indicate it as that of the ordinary ray, the symbol is $f_E{}^o$.

$f_{F_1}{}^x$ = critical frequency of the F_1 layer, extraordinary ray.

$f_{F_2}{}^x$ = critical frequency of the F_2 layer, extraordinary ray. The night portions of the $f_{F_2}{}^x$ curve are for the F layer. The symbols for F and F_2 at night are sometimes used interchangeably.

Variations With Time of Day and Season

No regular diurnal or seasonal variation is observed in the virtual height of the E layer, which appears to be almost always between 110 and 120 kilometers. The critical frequency of the E layer has however a regular diurnal and seasonal variation. It varies synchronously with the altitude of the sun, reaching the diurnal maximum at noon, and having a higher diurnal maximum in the summer than in the winter. This behavior accords with the simple theory of ionization by ultraviolet radiation from the sun, according to which, assuming recombination of ions to be sufficiently rapid,[9]

$$f_E = K\sqrt[4]{\cos\psi} \tag{4}$$

where ψ is the zenith angle of the sun, and K is a factor depending on the intensity of the solar radiation. This holds within fairly close limits for values of ψ not too close to 90 degrees, during the daylight hours of any one day.

No such simple relation characterizes the variation of the critical frequencies of the F, F_1, and F_2 layers. As may be seen from figure 7, the daytime critical frequencies of the F_2 layer are much higher in the winter than in the summer (although reports from the southern hemisphere indicate that the reverse is true there), and the night critical frequencies are somewhat lower in winter than in summer. The diurnal maximum of the F_2 critical frequency almost always occurs after noon, and is much later in the day in summer than in winter. The post-sunset drop in the night F critical frequency is much more rapid in the winter than in the summer; indeed in summer the midnight F critical frequency is sometimes as high as the noon F_2 critical frequency. The outstanding characteristics of the F_2 critical frequency are (1) a seasonal variation inverse to that of the E critical frequency, and (2) a diurnal lagging behind the altitude of the sun. The F and F_2 maximum critical frequency occurs in the winter day, and the minimum in the winter night. The day and night summer values are between these extremes.

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[7] "Multifrequency Ionosphere Recording and Its Significance," T. R. Gilliland, Bureau of Standards *Journal of Research*, volume 14, 1935, page 283 (research paper 769); IRE *Proceedings*, volume 23, 1935, page 1076.
"Characteristics of the Ionosphere and Their Application to Radio Transmission," T. R. Gilliland, S. S. Kirby, S. E. Reymer, and N. Smith, Bureau of Standards *Journal of Research*, volume 18, 1937, page 645 (research paper 1001); IRE *Proceedings*, volume 25, 1937, page 823.
"Characteristics of the Ionosphere at Washington, D. C., January to May, 1937," T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer, IRE *Proceedings*, volume 25, 1937, page 1174.
"Characteristics of the Ionosphere at Washington, D. C., . . .," published each month in IRE *Proceedings* for the second month before, starting with the September 1937 issue.

[8] "Averages of Critical Frequencies and Virtual Heights of the Ionosphere Observed by the National Bureau of Standards, Washington, D. C., 1934–36," T. R. Gilliland, S. S. Kirby, N. Smith and S. E. Reymer, *Terrestrial Magnetism and Atmospheric Electricity*, volume 41, 1936, page 379. Similar summaries in each succeeding quarterly issue.

[9] Relation given on page 251 of "Radio Observations of the Bureau of Standards During the Solar Eclipse of August 31, 1932," S. S. Kirby, L. V. Berkner, T. R. Gilliland, K. A. Norton, IRE *Proceedings*, volume 22, 1934, page 247.

The F_2 layer also differs markedly from the other layers in having much greater height in the summer than in the winter. The F_2 layer acts as though it were expanded by the heat in summer, resulting in higher virtual height and also greater volume for a given number of ions and thus lower ionization density and lower critical frequency. This is not a complete explanation, as the F_2 layer has many other anomalies, for example, a slight drop of critical frequency in midwinter from the seasonal maximum.

Year-to-Year Variations

Superposed on the variations of the ionosphere characteristics with season are the long-time variations with the solar cycle, caused by the rising and falling in an 11-year cycle of the sun's ultraviolet radiations. Practically the entire period of the observations under discussion, 1933 to the present, has been one of increasing solar radiation, as we are now at about the top of the cycle. There has consequently been an increase from year to year in the ionization and the critical frequency of all the layers. The trend reversed in 1938 and the critical frequencies will in general decrease until about 1944.

The heights of the various layers do not change appreciably from year to year. The chief change in respect to them is the disappearance of daytime F-layer stratification in the winter as the solar cycle advances. Thus, figure 7 shows no F_1 layer in December 1936, whereas in 1933 to 1935 there was a stratification into F_1 and F_2 layers in winter as well as in the summer although the stratification was much less marked in the winter than the summer.

Both seasonal and year-to-year changes of the E-layer critical frequency are shown in figure 8, curve b. This gives the average f_E at noon for each month. The full-line curve b shows the rise each summer and drop each winter, the climb to higher values each year, and also some minor fluctuations. To examine these three things separately, it is possible to redraw the curve with the seasonal variations eliminated, and this has been done. By means of equation 4, it is possible to calculate the value of the E-layer critical frequency at that point on the earth's surface where the sun's radiation is perpendicular; this is K, or $f_E/\sqrt[4]{\cos\psi}$, and it is plotted as the dashed curve.

For comparison, curve a gives average sunspot numbers for each month. The spots on the sun increase in number and activity as the solar cycle progresses, and it is believed that the intensity of the ultraviolet radiations causing the ionization of the layers of the ionosphere increases along with the sunspots. Neither the sunspots nor the ultraviolet radiations are the cause of the other, but both are manifestations of those profound activities within the sun which undergo the 11-year variation. It is not possible to compare directly against measured ultraviolet radiation from the sun because all the radiations which produce the ionosphere phenomena are absorbed in the ionosphere and do not reach the surface of the earth. The comparison with sunspot numbers is merely a comparison with a crude index of solar activity, but it is of some value.

The detailed correspondence of the dashed curve b with sunspot numbers is in fact impressive. It shows not only that the E-layer ionization follows the general trend of the sunspot numbers, but that the detailed changes from month to month show a fair amount of agreement. There is also fair week-to-week but not day-to-day correlation.

The F_2 layer presents a more complicated picture, since purely terrestrial influences, such as the temperature of the layer, play an important part. No such simple method therefore exists for eliminating diurnal and seasonal variations as may be done for the E layer. Figure 9 shows the variation, by average for each month, of the F_2 and F critical frequency for various parts of the day. The "midmorning" curve is for the time halfway between midnight and sunrise, and the "diurnal minimum" curve is for the time when the F critical frequency reaches its lowest value, about 30 minutes before ground sunrise. The midforenoon, midafternoon, and midevening curves are for times halfway between sunrise and noon, noon and sunset, and sunset and midnight, respectively. All of these curves show the general rise in critical frequencies superposed on the seasonal variation. The amplitude of the seasonal variation, as well as the average value, has risen each year, and is thus greater for greater solar activity. The high daytime values in winter, and high night values in summer, stand out. The midwinter dip in the daytime curves should also be noted. The diurnal minimum curve shows the least seasonal variation; this might be more or less expected, since the influence of the sun is least at this time.

Twelve-month running averages, which eliminate the seasonal variations, are given as dotted lines for the noon and the diurnal minimum values. They show more clearly the trend from year to year, and also make it easy to see the amplitude of the seasonal variations. It is interesting to compare them with the curve of sunspot numbers in figure 8.

The long-time trend of the ionosphere critical frequencies is shown more clearly in figure 10. The general trend parallel to that of the sunspot numbers is striking. All had their minimum in 1933 and maxi-

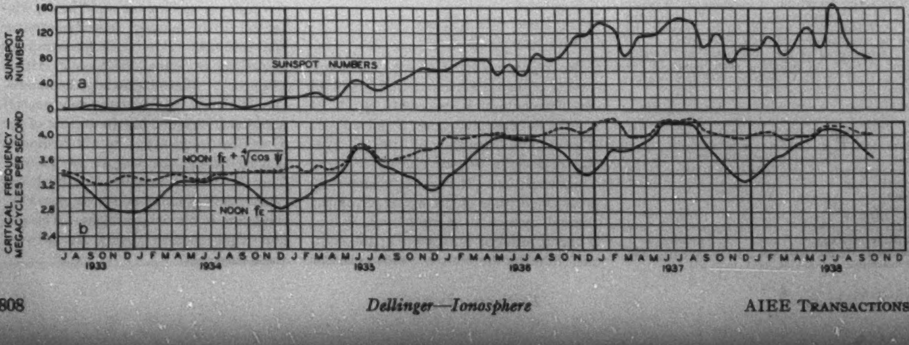

Figure 8. Variations of monthly average sunspot numbers and critical frequency of the E layer, 1933 to 1938

The solid curve (b) is the E-layer critical frequency as observed at Washington, and the dashed curve is the calculated E-layer critical frequency at the point where the sun's radiation is perpendicular

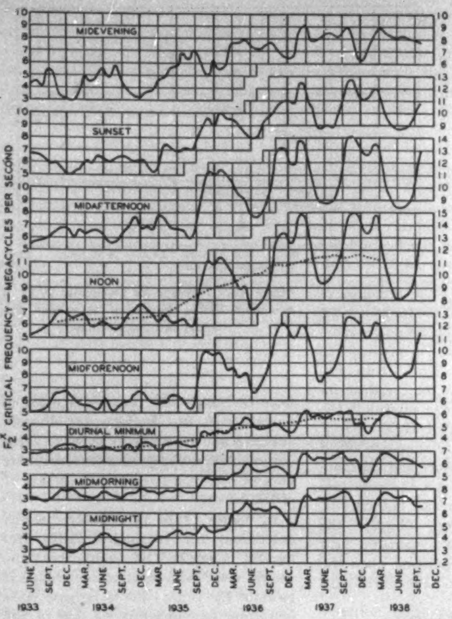

Figure 9. Variations of monthly average F_2 and F critical frequency, 1933 to 1938

mum in 1937. Again we see evidence that the sunspot numbers and the ultraviolet radiations which ionize the ionosphere have a close interrelation. The situation revealed in figure 10 is one of the most interesting of all the results yielded by radio-wave-transmission research.

Variations With Longitude and Latitude

The data presented in this paper are mostly those obtained in and near Washington, D. C., where the latitude is 39 degrees north. It is important to inquire how representative these are: are the ionosphere characteristics the same at other longitudes and latitudes? There is no a priori reason to expect any variation with longitude other than the large variations characteristic of the local time of day prevailing simultaneously at different longitudes. Ionosphere data from different longitudes in the same general range of latitude are limited. However, some information has been published in the past year, particularly from Japan,[10] and no material differences from the Washington data are found.

Latitude is quite another matter. It is to be expected that the varying angle of incidence of the solar radiations with latitude would lead to greater ionization in equatorial than polar regions. Data are limited; the available information[11] indicates that changes with latitude, other than those occasioned by the difference of season as the equator is approached or crossed, are not great. Measurements at latitude 12 degrees south indicate that the annual average critical frequencies (and thus the ionizations) are somewhat higher, and the virtual heights somewhat lower, than at Washington, 39 degrees north. There is relatively little seasonal variation near the equator. Measurements at latitude 70 degrees north, on the other hand, show lower average critical frequencies, and greater variations with season, than at Washington.

The variation with latitude is bound up with another effect, the occurrence of ionosphere disturbances, different types of which produce effects which are distributed differently in latitude. In particular, disturbances called "ionosphere storms," lasting a day or more and causing great changes in the F_2 layer height and ionization, are more intense and more frequent as the magnetic pole is approached. It is therefore important to separate days of this type from the undisturbed days, particularly when considering data from higher latitudes. This is discussed further in section IV.

III. Normal Radio Transmission

As explained in section I, some of the important facts of radio wave transmission over great distances are determinable from the characteristics of the ionosphere. We shall now inquire more carefully into the way in which this is done, and explain the application of these facts to practical radio-communication problems.

Relation of Oblique to Vertical Incidence

To compute long-distance radio data from ionosphere data is essentially to determine the relation between radio transmission incident obliquely on an ionosphere layer and transmission incident vertically on the layer. This is because ionosphere data are an expression of, and are determined by, radio transmission incident vertically on the ionosphere. When radio waves are transmitted over some horizontal distance, they are sent obliquely into the ionized layer, and as we have seen the ionized

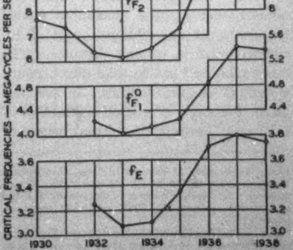

Figure 10. Comparison of annual averages of critical frequencies and sunspot numbers

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[10] "On the Long-Period Variations in the F_2 Region of the Ionosphere," K. Tani, Y. Ito, H. Sinkawa, *Report of Radio Research in Japan*, volume 7, 1937, page 91; also IRE *Proceedings*, volume 26, 1938, page 1340.
"Annual Variations in Upper-Atmospheric Ionization," K. Maeda, T. Tukada, T. Kamoshida, *Report of Radio Research in Japan*, volume 7, 1937, page 109.

[11] "Annual Variation of the Critical Frequencies of the Ionized Layers at Tromso During 1937," L. Harang, *Terrestrial Magnetism and Atmospheric Electricity*, volume 43, 1938, page 41.
"The Ionosphere at Huancayo, Peru, November and December 1937," H. W. Wells and H. E. Stanton, *Terrestrial Magnetism and Atmospheric Electricity*, volume 43, 1938, page 169.

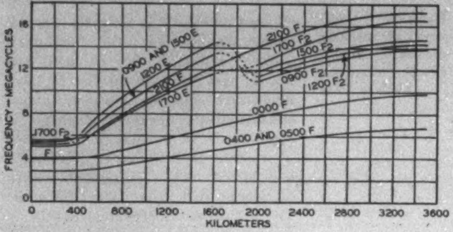

Figure 11. Average for June 1933 of maximum usable frequency at various distances and times of day

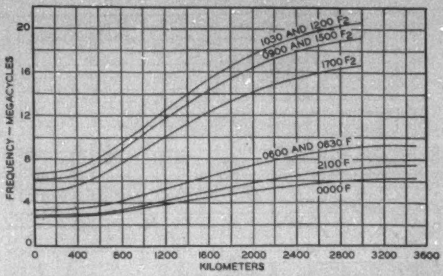

Figure 12. Average for December 1933 of maximum usable frequency at various distances and times of day

medium is able to reflect such waves of frequencies considerably in excess of the vertical-incidence critical frequency. As indicated by the approximate equation 2, $f_m = f_c \sec \phi$, a layer of given ionization density returns waves of frequencies which are higher, the greater the angle of incidence upon the layer. Thus, except as limited by the curvature of the earth, higher frequencies can be reflected the greater the distance of transmission and the lower the height of the reflecting layer.

In figure 1, for example, the *E* layer is shown reflecting a ray (1). Supposing the frequency to be the highest frequency which can be reflected by the *E* layer at that angle of incidence, then the ray (2) with a slightly smaller angle of incidence would not be reflected by the *E* layer but would penetrate it and go on up to the F_1 or F_2 layer and be reflected by one of them because of its greater ionization density. As the angle of incidence is decreased (angle of take-off increased), we arrive at a ray (3) which would not be reflected by the F_2 layer but would penetrate it and be lost to outer space. This is suggested by the arrow at the end of ray 3.

The approximate relation, $f_m = f_c \sec \phi$, gives a rough idea of the relation between f_c, the vertical-incidence critical frequency, and f_m, the maximum usable frequency, at any oblique angle of incidence, that is, at any distance. The exact relation[12] has to take into account a number of other factors. In the first place, the angle ϕ is itself a function of frequency, because the virtual height of the reflecting layer is a function of frequency. The higher the frequency the farther into the ionized layer do the radio waves penetrate. Thus, in figure 3 the virtual height rises slightly with frequency; this figure is for vertical incidence, and a similar rise appears in the relation for oblique incidence.

Secondly, the simple relation is modified because the earth's surface and the ionosphere layers from which the reflection takes place are not plane but curved, altering the geometry. Thirdly, the presence of the earth's magnetic field alters the relation, depending upon the length, direction, and location of the path of transmission.

All of these effects together make the calculation of maximum usable frequencies somewhat complicated. The National Bureau of Standards therefore publishes[13] curves of maximum usable frequencies as well as of critical frequencies in its monthly and other publications on the ionosphere. Examples are given in figures 11 to 14. Comparison of figure 14 with figure 6 shows how the simple secant relation or its equivalent, equation 1, is inadequate to represent the actual facts of radio transmission.

Maximum Usable Frequencies and Skip Distances

Figures 11 to 14 give the averages (for the days free from ionosphere storms) for the months shown, of the upper limits of usable frequencies, as a function of distance, for various times of day. The characteristic differences between summer and winter are shown, and also the striking increase of frequency with the advance of the cycle of solar activity during 1933 to 1937. This is what would be expected from the ionosphere changes depicted in figures 8 to 10. In fact, the diurnal, seasonal, and other effects shown in these curves follow directly from the ionosphere data of the type presented in section II of this paper.

In figures 11 to 14, the layer which determines the maximum usable frequency is marked on each curve. As shown, the *F* and F_2 layers determine it most of the time; this is because their ionization so much exceeds that of the lower layers. In the daytime in summer, however, the *E*-layer ionization is so great, and beyond a distance of about 500 kilometers the lower height of the *E* layer results in so much more oblique transmission, that the *E* layer is controlling. The curvature of the earth and of the *E* layer limits the reflection distance to about 1,700 kilometers; beyond that the F_2 layer is controlling as the curves show. The F_1 layer is seldom (summer day, for 2,000 to 3,000 kilometers) enough lower than the F_2 layer, and enough more ionized than the *E* layer, to determine the maximum usable frequency.

There are times when transmission does take place at frequencies higher than these critical frequencies, either because of "sporadic *E*" layer or scattered reflections. These special phenomena are discussed in section IV.

Each point on these curves not only gives the upper limit of frequency which is usable over the distance, but also conversely gives the lower limit of distance over which the frequency gives satisfactory sky-wave transmission. The curves thus serve the additional purpose of giving data on skip distance. Where skip distances are of primary interest, the relation between frequency, distance, and time of day may be more conveniently shown by curves of skip distance as a function of time of day, for various frequencies. Such a curve is shown in figure 15; it is for June 1937, and thus gives the same data as figure 13. Curves of skip distance against time, as in figure 15, are useful in selecting frequencies for a mobile radio station, such as an airplane or a ship, where the distance of transmission continually varies and it is necessary to determine a time and distance at which to change from one frequency to another.

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[12] "Application of Vertical-Incidence Ionosphere Measurements to Oblique-Incidence Radio Transmission," N. Smith, Bureau of Standards *Journal of Research*, volume 20, 1938, page 683 (research paper 1100).
"The Relation Between Atmospheric Transmission Phenomena at Oblique Incidence and Those at Vertical Incidence," G. Millington, Physical Society (Great Britain) *Proceedings*, volume 50, 1938, page 801.

[13] "Maximum Usable Frequencies for Radio Sky-Wave Transmission, 1933 to 1937," T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer, Bureau of Standards *Journal of Research*, volume 20, 1938, page 627 (research paper 1096); IRE *Proceedings*, volume 26, 1938, page 1347.
"Characteristics of the Ionosphere at Washington, D. C.,. . . . ," published each month in IRE *Proceedings* for the second month before, starting with the September 1937 issue.

Another useful form in which the data may be put is a set of curves of frequency as a function of time of day, for various distances. The data for June 1937 are shown in this form in figure 16. The curve for zero distance is identical with the curve of vertical-incidence critical frequency. Curves of this type are given in the monthly ionosphere reports of the National Bureau of Standards.[13] Such curves are useful in the operations of radio stations communicating between fixed points, as they are an aid in selecting the frequencies to be used during various times of day, for communication over a given distance.

Since all the curves change with time of day, and since on any long radio transmission path (except north-south) the time of day is different at all parts of the path, it is important to select the proper time of day in using these curves. The proper time is that of the locality where the waves reach, and are reflected by, the ionosphere. For paths in which the waves go from transmitter to receiver by a single reflection from the ionosphere, the place of reflection is halfway between transmitter and receiver.

Transmission by Multiple Reflections

It may be noted that figures 11 to 16 give no distances greater than 3,500 kilometers. The maximum possible distance of transmission by a single hop, that is, reflection from any ionosphere layer, is limited by the geometry of the earth's surface and the layers, and also by absorption at the ground of those waves which are nearly tangential. It is found in practice that the minimum angle with the ground of the radio waves transmitted or received averages about $3^{1}/_{2}$ degrees over land. From the geometry it results that the maximum distance along the earth by a single hop is ordinarily about 3,500 kilometers for the F_2 layer, and about 1,700 for the *E* layer. These may be exceeded in particular cases.

While the curves are drawn for single-hop transmission, they are nevertheless available for solving problems of multihop transmission, that is, multiple reflections from the ionosphere, with intermediate reflections from the ground. Calculation of the maximum usable frequency for multihop transmission is necessarily somewhat complicated. In the first place, we have to consider the time of day of the locality where each reflection from the ionosphere layer takes place. To a first approximation, the maximum usable frequency is the lowest one of the several corresponding to the times of day at the several localities where reflection takes place, for the distance on the curves equal to the transmission distance divided by the number of hops.

For very long paths, if very widely different latitudes are involved, it may be desirable to use curves appropriate to the latitude of each hop. As mentioned in section II, changes of ionosphere characteristics with latitude are not great, and it follows that the effect of latitude is of minor importance in radio transmission, except for extreme differences of latitude. In particular, for transmission within an area the size of the United States, or Europe, differences of latitude do not need to be taken into account. In transmission between the United States and Europe, however, although the difference of latitude may be no greater than within either area, the ionosphere characteristics vary materially along the transmission path from another cause. This is the effect of propinquity to the north magnetic pole. Certain ionosphere disturbances, as mentioned in section II, are more intense and more frequent as the magnetic pole is approached. There may also be a steady or permanent set of ionosphere effects having a maximum at the magnetic pole. See in this connection section IV.

For very long paths in which widely different longitudes (that is, times of day) are involved, it sometimes happens that the waves travel different parts of the way by different layers. For such cases, it is necessary to take account of the

Figure 13 (below). Average for June 1937 of maximum usable frequency at various distances and times of day

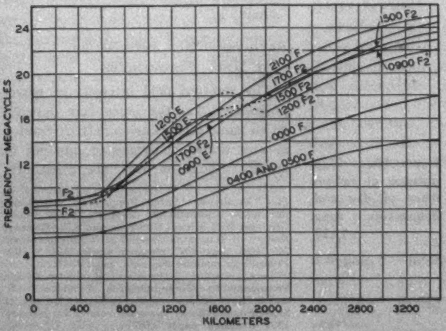
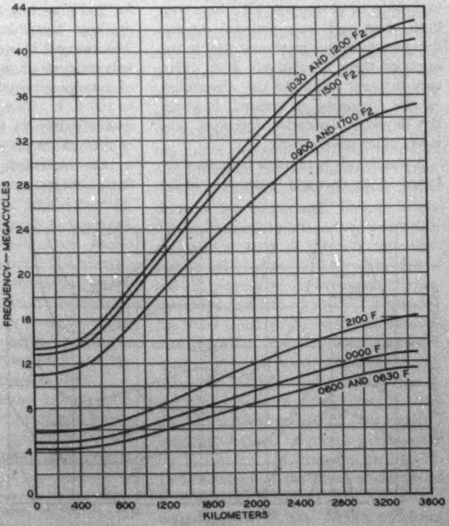


Figure 14. Average for December 1937 of maximum usable frequency at various distances and times of day



heights of the different layers to determine the lengths of the several hops, and also to employ separate curves of maximum usable frequency for each layer.

The waves reaching a given point may be a combination of waves having traveled by different numbers of hops. For each of these it is necessary to take account of the time of day, and to consider which layer is effective, for the locality where each reflection from the ionosphere occurs.

Optimum Frequencies

It is necessary to inquire whether the maximum usable frequency is the optimum frequency. It is found in practice that in general (especially in the daytime) the absorption is greater, that is, received intensities are less, as the frequency is lowered below the maximum usable frequencies. Thus it requires much greater power to get communication through on frequencies very much below the maximum usable. On the other hand, a frequency should be chosen somewhat below the values indicated in the curves of monthly averages because of the variability from day to day, which is generally within 15 per cent.

Fair efficiency of communication is usually provided in the daytime by frequencies down to about 50 per cent of the maximum usable frequencies, and at night by frequencies down to somewhat less than 50 per cent of the maximum usable frequencies. Definite limits cannot be set because there are large irregular variations of absorption with time over both short and long periods. At frequencies near the maximum usable frequencies there is relatively little difference between night and day absorption. As the frequency is lowered, however, the daytime absorption increases relatively much more rapidly.

A simple rule is to use a frequency between 50 per cent and 85 per cent of the monthly average maximum usable frequency for the given distance and time. It is not ordinarily possible to keep changing frequency continuously so some such range of choice is necessary. Below 50 per cent, the received waves are likely to be too weak for use, and above 85 per cent communication will be impossible on some days.

Interesting examples of the calculation of frequencies to be used for practical radio transmission, from the graphs of maximum usable frequency, have been published[14] recently.

Experimental confirmation of the validity of these calculations and these considerations of the relations between ionosphere characteristics and radio transmission conditions is given by extensive experience of radio stations and also by special experiments. The National Bureau of Standards continuously records the intensity of radio waves received from a number of stations at various frequencies and distances, in order to investigate this.

An example of the type of evidence given by these recordings is given in figure 17. The upper part of the figure is a continuous record of the field intensity of W6XKG, Los Angeles, Calif., on 25,950 kilocycles per second, at a distance of 3,700 kilometers. The lower part of the figure gives graphs of the calculated maximum usable frequency over this distance, for both one- and two-hop transmission. This distance is slightly beyond the ordinary maximum distance for good one-hop transmission, and the one-hop transmission is thus weak. The changes between one- and two-hop transmission are well marked; the ratio of average received intensity is as great as 100 to 1. This difference in intensity is due partly to the unfavorable angle of take-off for the single hop, and partly to the increased absorption over the flatter trajectory. It should be noted how the times of beginning and ending of two-hop transmission agree with the times the calculated maximum usable frequency passed through about 26 megacycles per second at the western and eastern hops, respectively: that is, the two-hop transmission began as soon as the western hop permitted and ended when the eastern hop failed. After the failure of two-hop transmission at 1,850 (evening), the station came in weakly by one hop. As the evening progressed (after 1,850) the intensity increased, owing to the departure of the daytime absorption and the rise in height of the layer, with a consequent more favorable angle of take-off. The failure of single-hop transmission at 2,030 is seen to agree with the time of diminution of the calculated maximum usable frequency through 26 megacycles per second. (The very low intensity after 2,030 is electrical noise, that is, atmospheric disturbances or "static.")

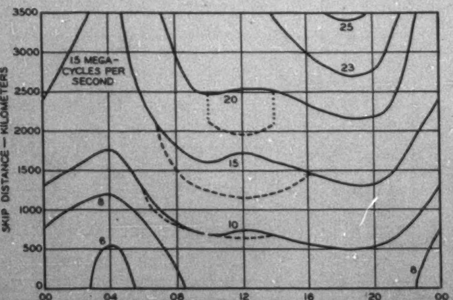


Figure 15. Skip distance at various times of day and frequencies, June 1937

Solid curves—*F* layer

Dashed curves—*E* layer

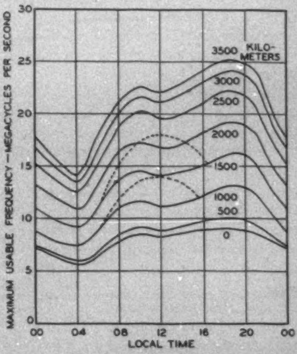


Figure 16. Maximum usable frequency at various times of day and distances, June 1937

Solid curves—*F* layer

Dashed curves—*E* layer

Received Field Intensities at High Frequencies

The received field intensity of waves propagated via the ionosphere depends on so many factors as to defy expression in any simple summary or any set of graphs. Data on this are constantly

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[14] "Maximum Usable Frequencies for Radio Sky-Wave Transmission, 1933 to 1937," T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer, Bureau of Standards *Journal of Research*, volume 20, 1938, page 627 (research paper 1096); IRE *Proceedings*, volume 26, 1938, page 1347.
"The Application of Graphs of Maximum Usable Frequency to Communication Problems," N. Smith, S. S. Kirby, T. R. Gilliland, Bureau of Standards *Journal of Research*, volume 22, January 1939 (research paper 1167).

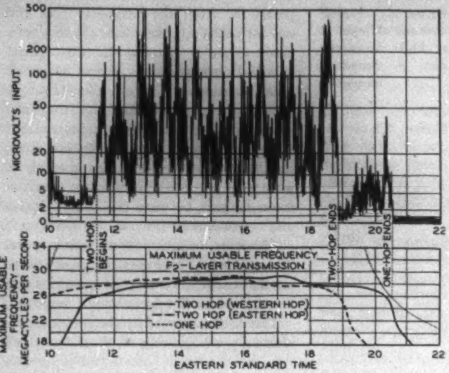

Figure 17. Example of effect upon received intensity of change of transmission from one to two hops and back to one hop

January 26, 1938; W6XKG, 25,950 kilocycles per second, Los Angeles, Calif.; 3,700 kilometers from Meadows, Md.

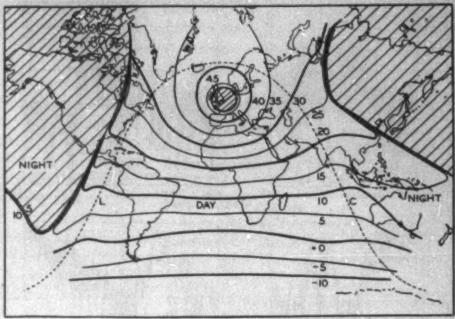

Figure 18. Sample diagram of lines of equal average received intensity for a particular frequency, time of day, season, epoch of solar cycle, and location of transmitter

The numbers are quasi-maximum field intensities expressed in decibels above one microvolt per meter, for one kilowatt radiated. The dotted line is the locus of sunrise (*L*) and sunset (*C*). The shaded areas are regions of zero reception

f = 18.8 megacycles per second (16 meters); winter, 1200 local time

being accumulated in the daily operations of radio stations and in such special recording laboratories as the National Bureau of Standards. As such data are analyzed they are found to be consistent with the ionosphere facts such as are reported in this paper, but detailed connections are limited because of the lack of direct measurements of ionosphere absorption. However, the facts of received field intensities are adding to our knowledge of the ionosphere, as just illustrated in the discussion of figure 17.

Data on the received field intensities of waves propagated via the ionosphere, as obtained in connection with the operations of radio stations, have been published in numerous articles.[15] Since sky waves exhibit great fading, the intensities constantly fluctuating over a great range, it is necessary to deal with averages. A convenient form of average for this purpose is the quasi-maximum, which is the value exceeded by the instantaneous value of the field intensity five per cent of the time.

An attempt was made to summarize a fairly large body of such information in the 1937 London Report of Committee on Radio Wave Propagation.[16] In a series of 18 figures, it gives contour lines of field intensity on a world map for two frequencies (8,600 and 18,800 kilocycles per second), for three times of day, for one epoch of the solar cycle, 1929–32, and for the transmitter (or receiver) located at London. For other locations of transmitter (or receiver) the data would be different, both because of different latitude and different distance from magnetic pole. The data given do not apply to times of ionosphere storms or other vagaries. One of these figures is reproduced here as figure 18. It gives received intensities for one kilowatt radiated from the transmitter. The curves are averages of values varying over a wide range. No set of graphs or tables would be adequate to give the facts of transmission for all frequencies, times, and other conditions.

Received intensities are largely dependent on the absorption of the wave energy in the ionized parts of the atmosphere below the ionized layer which reflects the waves. The absorption in general increases as frequency is decreased below the maximum frequency transmissible via a given layer. The absorption determines the minimum usable frequency and the maximum distance of communication, just as the ionization density or critical frequency determines the maximum usable frequency and the minimum distance (skip distance).

The absorption is found to vary with time of day, season, frequency, and length of path. It is usually greater during the day than during the night. It is greater during the summer day than during the winter day. A given frequency at large angles of incidence (long distance) behaves, with respect to absorption, like a much lower frequency at small angles of incidence (short distance).

Definite information about absorption and other characteristics of transmission via the different layers is given by continuous graphical records of received intensities. To illustrate the type of information given by many thousands of such graphs which have been recorded, two examples are given in figure 19. The top pair of graphs shows morning and evening intensities of reception from a station on 6,060 kilocycles per second at a distance of 648 kilometers. Shortly before 0700 (morning) there is a sharp increase in the general level of received intensity, and shortly before 1800 (evening) there is a sharp decrease and change in character of the received intensity. These are the times at which the radio transmission changed from *F* to *E* layer and vice versa. It follows that at these times the maximum usable frequency via the *E* layer for a distance of 648 kilometers was 6,060 kilocycles per second. The vertical-incidence critical frequency corresponding to this is 2,450 kilocycles per second. Determination of the times of change of layer from such records gives a means of determination of the vertical-incidence

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[15] A few examples are:
"Some Measurements of Short-Wave Transmission," R. A. Heising, J. C. Schelleng, G. C. Southworth, IRE *Proceedings*, volume 14, 1926, page 613.
"Short-Wave Wireless Telegraphy," T. L. Eckersley, IEE (London) *Journal*, volume 65, 1927, page 600.
"The Propagation of Short Radio Waves Over the North Atlantic," C. R. Burrows, IRE *Proceedings*, volume 19, 1931, page 1634.
"Attenuation of Overland Radio Transmission in the Frequency Range 1.5 to 3.5 Megacycles per Second," C. N. Anderson, IRE *Proceedings*, volume 21, 1933, page 1447.

[16] "Report of Committee on Radio Wave Propagation," IRE *Proceedings*, volume 26, 1938 page 1193.

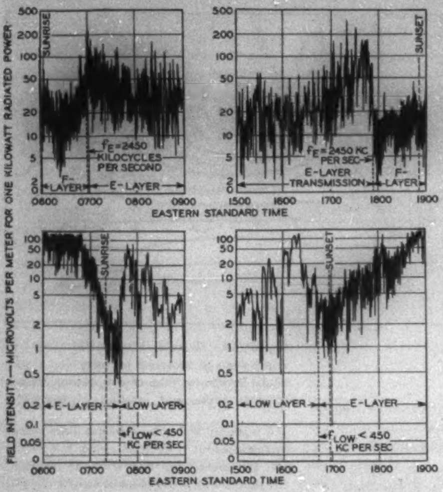


Figure 19. Typical changes of layer at a high frequency and a broadcast frequency

Top — W8XAL, Mason, Ohio; frequency 6,060 kilocycles per second, distance 648 kilometers; April 7, 1936

Bottom — WTIC, Hartford, Conn.; frequency 1,040 kilocycles per second, distance 480 kilometers; January 16, 1937

critical frequencies at particular times. This is the reverse of the process by which the graphs of maximum usable frequency described above were obtained.

Broadcast-Frequency Sky Waves

Referring further to figure 19, the lower pair of graphs shows the morning and evening intensities of reception from a broadcast station, on 1,040 kilocycles per second at a distance of 480 kilometers. At about 0740 in the morning there is a change of character and the start of a rise in intensity, and at about 1640 in the evening there is a marked change of character followed by a rise in intensity. These may be interpreted as the times at which the radio transmission changed from the *E* to a lower layer, and vice versa, and thus the times at which a layer below the *E* layer had a maximum usable frequency of 1,040 kilocycles per second for the distance of 480 kilometers. From this it may be calculated that the vertical-incidence critical frequency of the low layer is something less than 450 kilocycles per second; the exact value cannot be computed from this one observation because the height is not known. This shows that there is a layer below the *E* layer by which waves of broadcast frequency are reflected in the daytime. (In the summer the absorption is so great there is no transmission via the ionosphere at broadcast frequencies greater than about 1,000 kilocycles per second.)

This low layer may be called the *D* layer. Little is known about it, as ionosphere measurements have not been made directly upon it. Its properties are inferred from data of the kind shown in figure 19.

There is considerable empirical information on received sky-wave intensities at night on broadcast frequencies (which in Europe are from 150 to 1,500 kilocycles per second), for distances out to about 4,000 kilometers, and limited information for distances out to about 15,000 kilometers. For these frequencies the known facts can be expressed very simply, since to a first approximation the received intensity is the same for different frequencies and times of year, and at great distances is practically independent of ground conductivity. A curve of quasi-maximum values of received intensities at night on broadcast frequencies, for one kilowatt radiated from the transmitter, is given in figure 20. The same information on an expanded scale, for a part of the distance range, is given in figures 21 and 22. These two figures are for two typical cases of ground conductivity σ, stated on the figures in electromagnetic units.

The divergences of the curves in figures 21 and 22 for distances less than about 400 kilometers arise merely from the fact that at those distances the ground wave contributes appreciably, while at greater distances the received intensity is due entirely to the sky wave, that is, the wave propagated by reflection from the ionosphere.

The curve splits into two for distances beyond about 1,400 kilometers, one for paths far from the magnetic pole and one for paths relatively near the magnetic pole. This is because of the special effects in the vicinity of the magnetic pole mentioned above. The effect is very large. For instance, for transmissions between the United States and Europe, a distance of say 6,000 kilometers, the intensities are less than a tenth of what they are for transmissions over the same distance between the United States and South America.

There are variations from year to year. The evidence indicates that sky-wave intensities at broadcast frequencies are less in years of high sunspot numbers.

The data expressed by the curves represent only a beginning of effort to reduce this complex subject to quantitative form. The data for distances from 4,000 to 12,000 kilometers are based on measurements which although extensive, and averaged for several years, were all made at one time of year, early morning in the winter; it is not known to what extent they are representative for other times of the night and year. Incidentally, the practical importance of this is reduced, as far as east-west transmission is concerned, because night conditions remain only a short time over the whole of a very long path, particularly in the summer; furthermore there is little broadcasting after midnight at any one place, and thus time differences in the broadcasting tend to prevent interference.

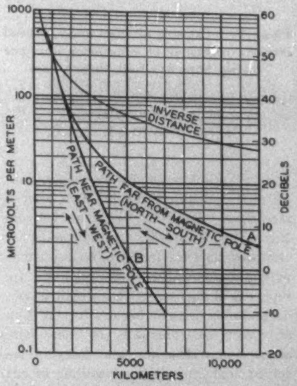


Figure 20. Received field intensity at night over great distances on frequencies from 150 to 1,500 kilocycles per second

Quasi-maximum for one kilowatt radiated

For the significance and limits of application of these curves, see text

The Contributions of the Several Layers to Practical Transmission

It is extremely hazardous to generalize about the intensity or the satisfactoriness of radio reception at different seasons, different ranges of frequencies, etc. A simple summary is impossible because (*a*) the constant changes of conditions in each layer are much too complicated, (*b*) radio transmission changes from one layer to another, and (*c*) the facts of absorption are largely unknown. Further complications are the various irregularities described in section IV. Furthermore, the satisfactoriness of reception is determined by other factors besides the received field intensity, notably the intensity of received noise or atmospheric disturbances. Noise itself exhibits complicated variations with time of day, season, place, etc.; a discussion of noise and its effects on radio reception is outside the scope of this paper.

Some information on what layers are effective in radio propagation at various ranges of frequencies is given in the curves of maximum usable frequencies, such as figures 11 to 16, but not full information.

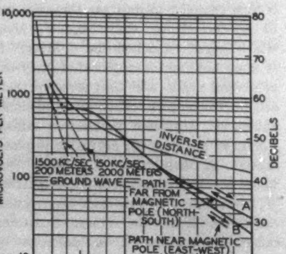


Figure 21. Night field intensity on frequencies from 150 to 1,500 kilocycles per second, for propagation over sea water

$\sigma = 4 \times 10^{-11}$ electromagnetic units

Quasi-maximum for one kilowatt radiated

For the significance and limits of application of these curves, see text

When the maximum usable frequency is transmitted by the F_2 layer, for instance, the curves give no information as to how effectively a lower layer may be serving at the same time as the means of transmission for lower frequencies. Thus in fact most long- and medium-distance communication in the summer is via the *E* layer; this is in part occasioned by the frequent occurrence of sporadic *E*. The F_1 layer is normally useless for radio transmission except for narrow ranges of distance and frequency, and need seldom be considered; this is because it is seldom enough lower than the F_2 layer and enough more ionized than the *E* layer to serve as the transmitting medium, particularly for considerable distances.

Daytime sky-wave transmission at broadcast frequencies is via the *D* layer. Night-time transmission at broadcast frequencies is principally via the *E* layer. At frequencies higher than about 1,000 kilocycles per second and particularly for the shorter distances, it is commonly via the *F* layer; this is particularly true in winter, sporadic *E* transmission replacing the *F* during much of the summer.

Specific information as to the layer which is operative in transmitting a particular frequency over a particular distance at a particular time is given by actual records of received intensities such as figures 17 and 19; there is, of course, as previously mentioned, no way of compressing all the information from such records into a simple summary. When the facts of radio transmission are examined, it is found that in general they follow very nicely from the facts of the ionosphere and the interpretations given here.

IV. Effects of Ionosphere Irregularities

The primary effects of the ionosphere on radio-wave propagation are those already described, which are due to the normal or regular characteristics of the ionosphere. The modes of variation of those characteristics have been shown to be of a regular and fairly predictable nature. There are some other ionosphere phenomena which are irregular in their nature and make radio phenomena in general much less predictable. Five types of such phenomena have been identified; sporadic *E*-layer transmission, scattered reflections, sudden ionosphere disturbances, prolonged periods of low-layer absorption, and ionosphere storms. The last three are probably due to irregular radiations of various types from the sun. The nature and origin of the first two are less well known; study of them must consider diffusion processes in the ionosphere as well as emanations from the sun and stars, meteors, and perhaps other agencies. The last three are primarily due to irregularities in time, while the first two are primarily due to irregularities in space; the space irregularities are patches or "clouds" in the ionosphere.

It is only recently that these irregularities have been well enough identified to be distinguishable from one another and from some of the regular ionosphere variations such as changes of critical frequency and consequent change of layer in radio transmission. This is another reason, besides the one cited in section II, why the present is a good time to summarize the facts of the ionosphere and their effects in radio transmission.

Sporadic E

It sometimes happens that waves are reflected by the *E* layer on frequencies higher than that at which the *E*-layer waves normally disappear and the reflection of waves by higher layers begins; for instance, in the example shown in figure 3 waves may sometimes be reflected at the *E*-layer height of 110 kilometers by frequencies higher than 3,000 kilocycles per second. These reflections are due to a different process than the normal reflection in the ionized layer; the process is probably one of reflection from a sharp boundary of stratified ionization. The existence of these "sporadic *E*" reflections necessitates a redefinition of the term "critical frequency," previously defined as the highest frequency at which signals are received back from the layer. When sporadic-*E* reflections occur they may be received simultaneously with reflections from higher layers; thus, for example, in the case shown in figure 3, vertical-incidence reflections might be received at 8,000 kilocycles per second from both the *E* and the F_2 layers. The *E*-layer critical frequency, more precisely defined, is the value (3,000 kilocycles per second in

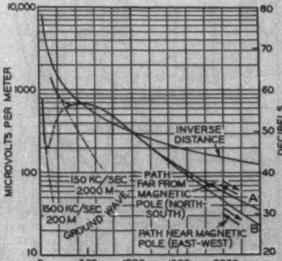


Figure 22. Night field intensity on frequencies from 150 to 1,500 kilocycles per second, for propagation over land of average conductivity

$\sigma = 4 \times 10^{-13}$ electromagnetic units

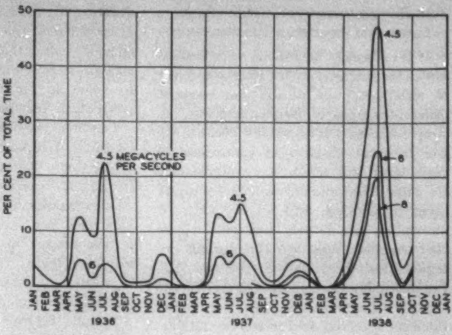
Quasi-maximum for one kilowatt radiated

For the significance and limits of application of these curves, see text figure 3) at which the observed virtual height shows a sudden rise to very large values as the frequency is increased. Except for the occurrence of sporadic-*E* reflections, all waves of higher frequency pass through the *E* layer and are not reflected by it.

The action of sporadic *E* may be analogous to partial reflection in optics while the regular ionosphere layer action is analogous to total reflection in optics. The sporadic *E* is confined to limited regions, like clouds or patches, in the *E* layer which have a very sharp boundary. These patches may be from perhaps one kilometer to several hundred kilometers in extent. Waves reaching them are reflected, even when of frequencies much higher than the *E* critical frequency. Sporadic *E* is thus patchy in space as well as sporadic in time, so that its name is well justified.

Figure 24. Variation of the prevalence of sporadic E, 1936 to 1938

Per cent of total time of observations on 4, 5, 6, and 8 megacycles per second; 6-megacycle observations begin April 1936, 8-megacycle observations begin August 1937



Sporadic *E* leads to interesting results in radio transmission. It accounts for long-distance transmission up to higher frequencies than by any other means. The maximum vertical-incidence frequency for which strong reflections by sporadic *E* have been found is about 12 megacycles per second. By reason of the large angles of incidence possible with the *E* layer, this has made long-distance communication possible on frequencies as high as 60 megacycles per second. Such communication is generally for only a short time and for restricted localities. For example, on a particular day a patch of sporadic *E* intense enough to reflect 56-megacycle transmissions was found to be somewhat larger than the state of South Carolina, as shown in figure 23; transmissions from distant points by a single hop, at such distances from a receiving point that they were reflected from this patch over the general vicinity of South Carolina, were received on frequencies as high as 56 megacycles per second. Transmissions reflected from outside this patch were limited to lower frequencies determined by the normal ionosphere ionization.

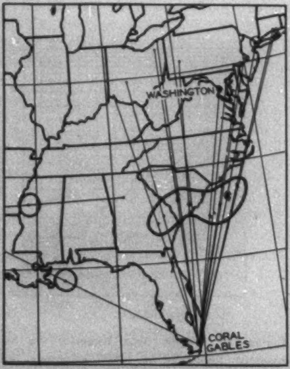


Figure 23. Location of large patch of sporadic E by reception of numerous transmitting stations over long distances

Points of reflection for 56-megacycle transmissions on May 15, 1938, reported by W4EDD, Coral Gables, Fla.

Sporadic *E* occurs most commonly in the summer, particularly in the morning and evening but may occur any time of day or night. It occurs occasionally at all seasons, particularly in the evening. Detailed information on its prevalence is published each month in *Proceedings* of the Institute of Radio Engineers by the National Bureau of Standards. A summary of known data is given in figure 24, expressed in terms of vertical-incidence transmission. The figure shows its year-round occurrence, its greater prevalence in May, June, July, and August, and its variation from year to year. The prevalence of sporadic *E* has not increased uniformly with the advancing solar cycle, like the regular characteristics of the ionosphere, but it is believed to be more prevalent at sunspot maximum than sunspot minimum. Its occurrence is not correlated with other types of ionosphere irregularities nor with thunderstorms or other known phenomena. There is evidence that it occurs more at high than at equatorial latitudes.

SCATTERED REFLECTIONS

An irregular type of reflection from the ionosphere occurs at all seasons and both day and night. These reflections are most noticeable within the skip zone, or at frequencies higher than those normally receivable from the regular layers. Like sporadic *E*, they occur at frequencies which may exceed the F_2 critical frequencies, but are unlike sporadic *E* in that they are complex thus causing signal distortion. They are almost useless for communication purposes. Some types of them are of very weak intensity. The scattered reflections are characterized by very great virtual heights, usually somewhere from 400 to 1,500 kilometers. Their occurrence was for a time thought to indicate the existence of another layer above the F_2 layer which might be called the *G* layer. It is now, however, thought that they are of several types, and that some of them are due to complex reflections from small, ephemeral, scattered patches of ionization in or between the normal ionosphere layers. It has been suggested that some types of these ephemeral patches of ionization may be due to irregular radiations from the stars. Scattered reflections are shown in portions of figures 27, 28, and 30, as explained in the text referring to each.

SUDDEN IONOSPHERE DISTURBANCES

The most startling of all the irregularities of the ionosphere and of radio wave transmission is the sudden type of disturbance manifested by a radio fade-out. This phenomenon is the result of a burst of ionizing radiation from a bright chromospheric eruption on the sun, causing a sudden abnormal increase in the ionization of a portion of the ionosphere below the *E* layer, frequently with resultant disturbances in terrestrial magnetism and earth currents as well as radio transmission. The radio effect is the sudden disappearance of radio signals received on high frequencies.

The diminution of the radio signals to zero usually occurs within a minute. The effects occur simultaneously throughout the hemisphere illuminated by the sun, and do not occur at night. The effects last from about ten minutes to an hour or more, the occurrences of greater intensity in general producing effects of longer duration. The effects are more intense, and last longer, the lower the frequency in the high-frequency range (that is, the range from about 1,500 kilocycles per second up). The radio, magnetic, and other effects are markedly different from other types of changes in these quantities. The effects are most intense in that region of the earth where the sun's radiation is perpendicular, that is, greater at noon than at other times of day and greater in equatorial than in higher latitudes.

The effect is most striking. Frequently all "static" as well as the radio signals disappear. Many a radio operator has taken his radio receiver apart, thinking that some wire had become disconnected, and many a time it has been thought that a fuse had blown in the station, when one of these sudden fade-outs occurred.

An example showing both radio and magnetic effects is shown in figure 25. The four records of received field intensity from distant stations show that the radio intensity suddenly dropped from normal intensity to zero at 1758 Greenwich meridian time, that is, 12:58 p.m., Eastern standard time. This completely wiped out radio transmission throughout the hemisphere; reports to that effect were received from many points in the United States, also Europe and Japan. As shown, the effect lasted much longer on 6,060 kilocycles per second than on 9,570 kilocycles per second at about the same distance. It did not last longer on 9,570 than on 13,525 or 15,625 kilocycles per second because the distance (and the angle of incidence) was greater in the latter cases. As has been noted previously in other regards, effects on a given frequency for a short-distance path correspond to those on a higher frequency for a long-distance path.

Taking due account of the variation of the effects with frequency and distance, varying effects in differing directions can be explained. Reception in the United States from stations in the southern hemisphere usually exhibits greater effects than reception from other directions (because of passing the equatorial regions). Similarly, when the disturbance occurs at a time when it is morning at the receiving point the effects are usually greater in reception from the east than from the west, and vice versa for the afternoon (because of passing the region where it is noon). A radio fade-out sometimes occurs when it is night at the receiving point, but only when the path of the wave is somewhere in daylight.

The cause of the sudden disappearance of radio signals is the sudden production, by a burst of ionizing radiation from the sun, of abnormally great ionization below the *E* layer. This causes abnormally great absorption of radio waves passing through this ionized region on their way up to and down from the regular reflecting layers. The ionization of the regular reflecting layers is not affected.

There is some evidence that received waves of broadcast and lower frequencies increase rather than decrease in intensity during one of these occurrences. As such waves are reflected by, instead of passing through, an ionized layer of the atmosphere below the *E* layer, this is consistent with the explanation of the disturbance as due to increase of ionization below the *E* layer. It is not known at just what height the ionization is produced, but it may be in the *D* layer, mentioned in section III as the layer responsible for daytime broadcast transmission in the winter. The height of the *D* layer is probably from 50 to 90 kilometers at different times.

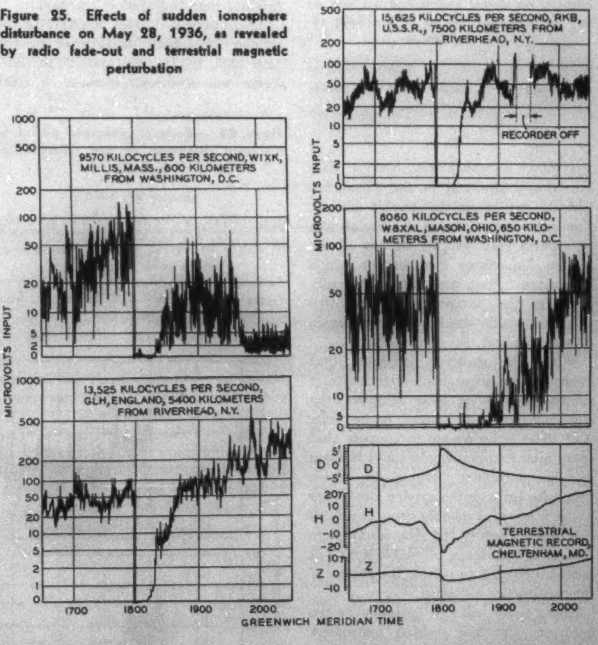


Figure 25. Effects of sudden ionosphere disturbance on May 28, 1936, as revealed by radio fade-out and terrestrial magnetic perturbation

The reason this abnormal ionization is produced low in the atmosphere and not in the regular reflecting layers (*E*, *F*, etc.) is doubtless because the solar eruptions emit some radiation of different frequencies from those of the steady radiations which maintain the ionization of the *E* and higher layers. This abnormal radiation is probably of such a frequency as to pass readily through the *E* and higher layers and be absorbed by the ozone which exists at heights from about 15 to 60 kilometers. The frequency of this radiation is presumably in the ultraviolet, nearer to the optical frequencies than those which produce the regular ionization of the *E* and higher layers.

Study of these effects is arousing great interest and focusing new effort upon the study of the sun. The sudden ionosphere disturbance is the only known instance in which a specific happening on the earth follows directly from a specific random happening on the sun or other heavenly body. The ionosphere gives information about some of the radiations from the sun which can be

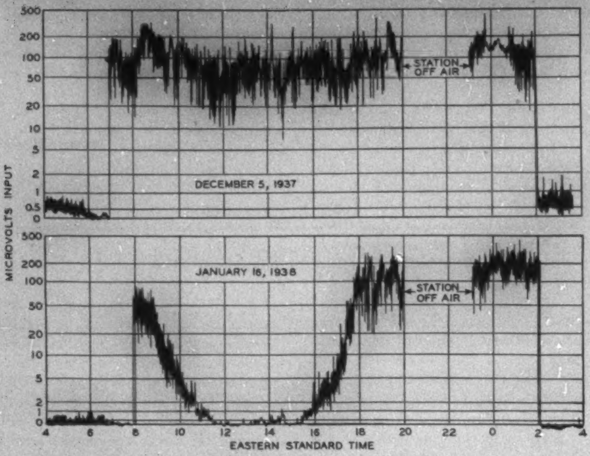


Figure 26. Comparison of recorded field intensity on normal undisturbed day and on day of prolonged period of low-layer absorption

W8XAL, Mason, Ohio, 6,060 kilocycles per second; 650 kilometers from Washington, D. C.

studied in no other way because they are wholly absorbed in the ionosphere and do not reach the earth's surface. The solar eruptions in particular can be studied very well by the aid of the sudden ionosphere disturbances which they cause. Such study may eventually elucidate the nature of the eruptive processes within the sun and the causes of sunspots and the 11-year cycle.

While the evidence indicates that every sudden ionosphere disturbance is accompanied by a solar eruption, the converse does not appear to be true. And there is no reason to suppose that every solar eruption would emit radiation of the particular frequencies which penetrate through the earth's ionosphere to the *D* layer. Probably many eruptions rise high enough in the solar atmosphere to permit the escape of visible light but not high enough to permit the escape of this ultraviolet radiation.

There is no seasonal variation in the occurrence of the sudden ionosphere disturbances or the solar eruptions which cause them. The solar eruptions produce the effect regardless of location on the sun's surface. An eruption usually, but not always, takes place near an active sunspot group. Most of the eruptions which produce sudden disturbances of the ionosphere are much brighter than the average eruption.

There were 17 known instances of the sudden ionosphere disturbance in the year 1935, 103 in 1936, and 220 in 1937. There was a similar increase of solar eruptions in these years, which were also years of increasing sunspot numbers. The variation of number of sudden ionosphere disturbances from week to week, and from month to month, corresponds fairly well with the number of solar eruptions, but not with the number of sunspots. Thus, just as we found in the case of the ionosphere critical frequencies (figure 10), the sunspot numbers show a year-to-year but not a short-time correlation.

Prolonged Periods of Low-Layer Absorption

This phenomenon is similar to the sudden ionosphere disturbance in its effects and characteristics except that its beginning as well as recovery is gradual and it has a longer time duration, commonly several hours. The intensity diminution is in general not as severe as in the more intense fade-outs, but sometimes the intensities at the medium high frequencies fall to zero.

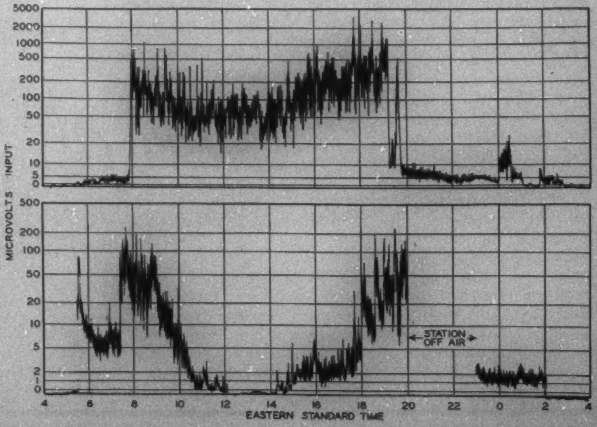
The phenomenon is illustrated in figure 26, which shows two field-intensity records of transmissions from a station on a frequency of 6,060 kilocycles per second, distant 650 kilometers from the point of reception. The upper graph, for December 5, 1937, is a record of a normal day. The average intensity goes down slightly during the middle of the day, indicating somewhat more absorption during the middle of the day than during the morning and evening hours. (The very low intensities at each end of each graph represent "static.") The lower graph, January 16, 1938, shows a prolonged period of low-layer absorption. Here the intensity falls gradually from

Figure 27. Effects of prolonged period of low-layer absorption on two different frequencies

January 27, 1938

Top—W1XK, Millis, Mass., 9,570 kilocycles per second; 600 kilometers from Washington, D. C.

Bottom—W8XAL, Mason, Ohio, 6,060 kilocycles per second; 650 kilometers from Washington, D. C.



the normal value at 0800 (a.m.) to zero, and is zero or very low for several hours, rising again to normal value at 1800 (6 p.m.). Except for the gradual beginning the effect is similar to the sudden ionosphere disturbances.

The different effects of this phenomenon at different frequencies are shown in figure 27. Both records are for the same day. The upper record, for a station on 9,570 kilocycles per second, shows some absorption, that is, reduction of intensity in the middle of the day. The lower record, for a station on a lower frequency (6,060 kilocycles per second) at about the same distance, shows very much greater absorption in the middle of the day. Thus, just as in the sudden ionosphere disturbances, the effects are less at higher frequencies if distance and other conditions are the same.

(Other phenomena shown in this figure are as follows. In the top graph, for W1XK: scattered reflections in the early morning until about 0800, then abrupt beginning of *F*-layer transmission as the ionization increases, abrupt failure of *F*-layer transmission as the ionization decreases at about 1910, then scattered reflections. The bottom graph, for W8XAL, shows: a burst of *F* layer at 0530, then scattered reflections until 0730, transmission until 1600, then F_2-layer transmission until some unknown time after 2000, then scattered reflections until 0200.)

Figure 28 shows that the simultaneous occurrence of low-layer absorption and sudden ionosphere disturbances is possible; in fact it shows two severe fade-outs happening during a prolonged period of low-layer absorption. The lower field-intensity record, for W8XAL, shows a period of low-layer absorption which reduced the received intensity to zero for several hours. Because this had already gone to zero it could not indicate the two intense fade-outs which occurred during this period. They appear, however, on the upper record, which is for a station of higher frequency (W1XK), because the low-layer absorption did not reduce the intensity at this higher frequency to zero. The simultaneous occurrence of these two phenomena was fortuitous.

The equivalent vertical-incidence frequency for station W8XAL was about 2,300 kilocycles per second and for W1XK was about 6,500 kilocycles per second. The reason that the vertical-incidence critical frequencies are not proportional to the transmission frequencies over nearly the same distance is that the two transmissions were reflected from layers of different heights, *F* and *E* layers respectively. This figure illustrates the value of the concept of equivalent vertical-incidence frequency in evaluating absorption over long paths. Records of vertical-incidence reflections at several frequencies are shown at the bottom of the figure. The reflections at 2,500 kilocycles per second were lost between 1100 and 1630 Eastern standard time because of low-layer absorption, so the fade-outs could not be shown at this frequency. The reflections at the higher frequencies were not eliminated by the low-layer absorption, and the loss of reflections between about 1300 and 1500 Eastern standard time indicates the fade-outs.

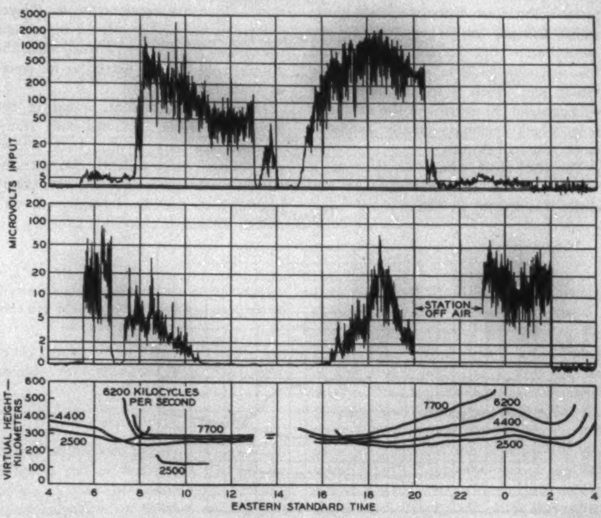


Figure 28. Occurrence of sudden ionosphere disturbances during a prolonged period of low-layer absorption

January 20, 1938

Top—W1XK, Millis, Mass., 9,570 kilocycles per second; 600 kilometers from Washington, D. C.

Center—W8XAL, Mason, Ohio, 6,060 kilocycles per second; 650 kilometers from Washington, D. C.

(Other phenomena shown in figure 28 are as follows. In the top graph, for W1XK: "static" from 0400 to 0530, then scattered reflections until about 0800, then F_2 transmission until 2030, then scattered reflections until 0100, then "static." In the bottom graph, for W8XAL, are shown: "static" from 0400 to 0530, then *F* transmission until 0615, then *E* transmission until 1820, then *F* transmission until 0200, then "static.")

The absorption causing the low-layer absorption effect appears to be due to ionization in a part of the ionosphere below the *E* layer, exactly as for the sudden ionosphere disturbances. The ionization is caused by an abnormally great outpouring of ultraviolet light from the sun, but in this case it is not so sudden as in the eruptions which cause the sudden ionosphere disturbances. The variation of the effects with frequency, and other characteristics, are the same as for the sudden ionosphere disturbances.

Both phenomena occur at all seasons, but the prolonged periods of low-layer absorption have been found to occur in a group of several weeks duration at periods of high sunspot activity, the groups being separated by more or less quiet periods of several months. They frequently but not always occur during periods when sudden disturbances of the ionosphere are numerous. They seem to occur more during years of large solar activity than at sunspot minimum.

Ionosphere Storms

An ionosphere storm is a period of poor radio transmission (except for the low frequencies, below 500 kilocycles per second, which are sometimes improved) lasting a day or more, and usually accompanied by a magnetic storm, that is, a period of unusual fluctuation of terrestrial magnetic intensity. It has two phases, an initial turbulent phase and a following moderate phase. Usually only the second phase occurs in medium and low latitudes. The initial turbulent phase is the cause of the moderate phase which follows, but is confined to the auroral zone, that is, the region around the magnetic pole in which aurora is visible and which is usually limited to within about 20 degrees of the magnetic pole, which region is greatly extended in very severe storms.

The turbulent phase consists of a violent boiling or turbulence of the entire ionosphere in the auroral zone, resulting in irregularly moving small clouds of ionization and a disintegration of the normal stratification of the ionosphere from the *E* layer on up. Whatever causes the storm apparently plunges into the ionosphere at auroral-zone latitudes, and literally tears it up. On the rare occasions when the auroral zone has extended as far south as Washington, an increase in *F*-layer ionization has been observed to precede the turbulent phase. This is consistent with the idea that the carrier of the energy of the ionosphere storm, when it first entered the high ionosphere, caused an increase in ionization. No consistent increase in *F*-layer ionization has been observed to precede the ordinary less severe storms, when the auroral zone did not extend as far south as Washington.

During the turbulent period of the ionosphere storm, high-frequency transmissions are very erratic, both signals and "static" surge violently, being transmitted with good intensity for short intermittent periods, interspersed with periods of complete failure. This indicates severe turbulence in the ionosphere with small unstable patches or clouds of high ionization densities. Such clouds may not be directly over the midpoint of the great-circle path and the transmission may not even be by a great-circle path.

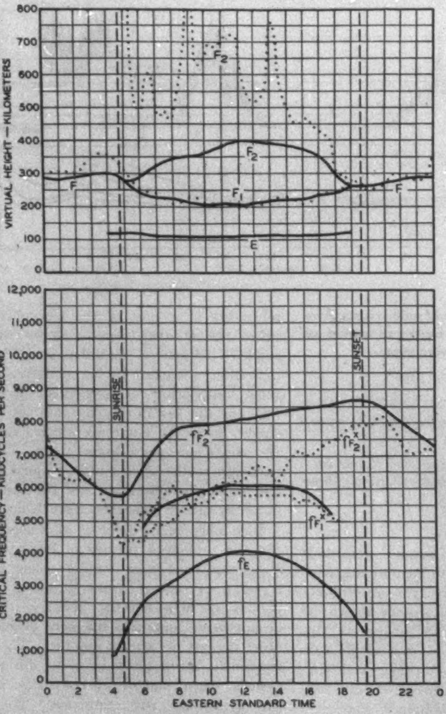


Figure 29. Comparison of ionosphere characteristics on a day of ionosphere storm and normal undisturbed days

June 1938

Solid curves—Average for undisturbed days

Dotted curves—June 8

The moderate phase, following the turbulent phase of an ionosphere storm, is characterized by an expansion and diffusion of the higher *F* region, extending into latitudes farther from the auroral zone, the greater the intensity of the storm. This expansion and diffusion of the ionosphere increases the virtual heights and lowers the ionization densities. This results in abnormally low critical frequencies and abnormally great virtual heights of the night *F* and daytime F_2 layers, and to a less extent of the daytime F_1 layer, and also increases the absorption, that is, reduces received intensities. (When the ionosphere storm occurs in a winter day, the normally unobservable F_1 layer appears.) The night *F* layer is more complex and turbulent than normal. Increased absorption of the *x* components of the daytime F_1 and F_2 layers is especially noticeable. The *E* layer is usually not appreciably affected. This moderate phase of the ionosphere storm extends to the latitude of Washington much more frequently than the turbulent phase. It lags behind the severe effects of the associated magnetic storm by several hours. During the moderate phase the ionosphere gradually returns to normal conditions, but this recovery also lags behind the associated magnetic storm's recovery.

The maximum usable frequencies for night *F*-layer and daytime F_2-layer transmissions are much reduced because of the lowered critical frequencies and increased virtual heights. Thus the higher frequencies are not usable. Frequencies low enough to be received are usually abnormally absorbed, especially during the daytime. There is usually increased fading and instability of transmissions over night paths. Sky-wave field intensities at broadcast frequencies rise much later at night and reach values much lower than normal.

Ionosphere storm effects diminish greatly with distance from the magnetic pole. Transmissions reflected from the ionosphere south of a radio receiving point may often be received satisfactorily while those reflected from the ionosphere farther north are not. Sometimes there appears to be a fairly sharp line of cleavage between the disturbed region (to the north) and the undisturbed (to the south). Transmissions which pass through the disturbed regions in the ionosphere are affected regardless of the direction of transmission.

In most ionosphere storms only the

second or moderate phase is experienced at any except very high latitudes. The principal effects of this phase may be summarized as: (*a*) increase of virtual heights of F, F_1, and F_2 layers, (*b*) decrease of critical frequencies of the same layers, (*c*) greater sharpness of F_1 critical frequency (*d*) decrease of maximum usable frequencies, (*e*) increase of skip distances, (*f*) increase of absorption (that is, decrease of received intensities). Effects (*a*) and (*b*) are illustrated in figure 29, which shows virtual heights and critical frequencies of a day of ionosphere storm (June 8, 1939) in comparison with the month's average of undisturbed days. The E layer was the same on June 8 as on the undisturbed days. Effects (*d*), (*e*), and (*f*) are illustrated in figure 30, which shows (at top) a graphical record of received intensity for a normal undisturbed day and (at bottom) a similar graph for a day of severe ionosphere storm; on the day of ionosphere storm the intensities were extremely low, even for the "static."

(Other phenomena shown in figure 30 are as follows. In the top graph: "static" from 0400 to 0600, then scattered reflections until 0700, then F_2 transmission until 2200, then scattered reflections until 0100, then "static" until 0400. In the bottom graph are shown: very weak "static" for a few minutes after 0400, then scattered reflections until 0700, then very weak "static" until 1130, then scattered reflections until 0100, then very weak "static." The top graph as recorded had values about three times higher from 1755 to 2205, because of a change of antenna at 1755; it is shown here as it would have been with constant antenna conditions.)

Ionosphere storms (and the magnetic storms that usually accompany them) have several characteristics the opposite of those of sudden ionosphere disturbances (and the magnetic perturbations that sometimes accompany them). The former are more intense the higher the latitude, while the latter are more intense the lower the latitude. The former occur both day and night, and the latter are confined to the day hemisphere. The former last one or more days, the latter usually last less than an hour.

These two types of ionosphere irregularity occur in general independently of one another but both are more likely to occur at times of great sunspot activity. They are more frequent and intense during years of sunspot maximum than sunspot minimum. A group of sudden ionosphere disturbances occurring on successive days is sometimes followed, after several days, by one or more ionosphere storms.

On account of their differences, different procedures are followed in practical radio communication to combat the effects of the two types of disturbance. When a sudden ionosphere disturbance occurs it may be possible to continue communication by shifting to a higher frequency; communication could also be accomplished by using a frequency lower than the broadcast range, but a change to such low frequency would in general be too cumbersome for the short time of the sudden ionosphere disturbance. During the turbulent phase of an ionosphere storm the only way to assure dependable communication is to use a frequency below the broadcast range. During the moderate phase of an ionosphere storm it may be possible to continue communication by shifting to a lower frequency within the high-frequency range.

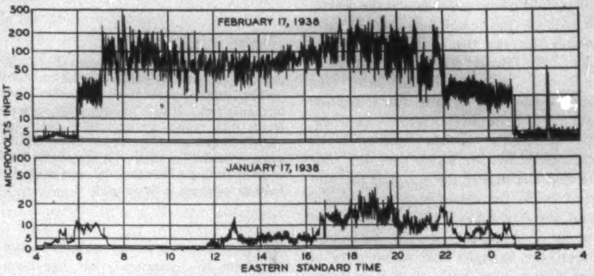


Figure 30. Comparison of received intensities on a day of ionosphere storm and on a normal undisturbed day

W1XK, Millis, Mass., 9,570 kilocycles per second; 600 kilometers from Washington, D. C.

V. Conclusion

The ionosphere is a new world to which radio research and radio operations have given us access in the past few years. A broad survey of this vast territory has been given in the present paper; many important features of the new territory have been neglected or barely mentioned.

I have summarized the work of many men and institutions. The nature of the paper forbade the individual crediting of most data and results to the originators. Splendid work has been done by the ionosphere pioneers (scientists and engineers) who have created the body of knowledge here reported. I am especially indebted to my colleagues in the National Bureau of Standards upon whose work I have drawn most heavily: S. S. Kirby, T. R. Gilliland, N. Smith, F. R. Gracely, and A. S. Taylor.

Short-distance radio transmission by means of the ground wave is not included in this paper, which is limited to the sky wave. Thus the important domains of very low frequencies and ultrahigh frequencies are not covered. The ground wave is calculable and is relatively unvarying with time; its phenomena are not so complicated or interesting as the sky waves. It is by use of the sky waves that nearly all long-distance radio communication is carried on.

This paper also does not include the subject of atmospheric disturbances (that is, natural electrical noise or "static"). They are themselves radio waves, originating principally in distant lightning flashes, and propagated by the same mechanisms as other radio waves. As their effects are largely produced by waves traveling in the ionosphere, much of the information presented in this paper is applicable to their study.

This paper has shown how sky-wave transmission is determined by, and calculable from, the heights and ionization densities and other properties of the ionosphere layers. The maximum usable frequencies at any distance, for instance, are directly determinable from the virtual heights and critical frequencies measured in vertical-incidence experiments. Optimum frequencies may be similarly estimated, though not as certainly as the maximum usable frequencies. The received intensities of the waves may be estimated to a certain extent from ionosphere data, but much more extensive data are needed for this purpose. Study of the behavior of the ionosphere during the five types of irregularities or anomalies discussed in section IV greatly clarifies our understanding of certain radio phenomena, and leads to knowledge of how to overcome transmission difficulties.

Examination of the facts and relations of radio wave propagation via the several layers of the ionosphere should give ample warning that it is hazardous to generalize about good and bad radio reception. Any conclusion must take into account the heights and ionization densities of the several layers concerned, the absorption at the various levels through which the waves pass, the time of day, the season, the epoch of the sunspot cycle, the distance of transmission and angle of take-off of the waves and angle of incidence at the ionosphere layer, the latitudes and propinquity of the transmission path to the magnetic pole, and the occurrence of ionosphere disturbances and irregularities.

The more one views the complexities of radio transmission via the ionosphere, the more he marvels that it provides any intelligible communication. However, as the facts of the ionosphere become better known, and the mechanism of reflection of radio waves from the ionosphere layers is more fully worked out, it becomes more nearly possible to assure long-distance radio transmission at all times. To this end it is fortunate that a beginning has been made on an ionosphere-data reporting service. As this is extended, it will be easier to predict radio-transmission conditions for a given time and path. The reliability of such prediction should surpass that of weather, for the controlling factors are better known and more uniform. Both weather and ionosphere phenomena are due primarily to the sun, but the sun's effects are more direct and more uniform over the earth for the ionosphere than for weather. The weather, incidentally, has no relation to ionosphere phenomena, being produced in much lower regions of the atmosphere.

Study of the ionosphere not only provides means of improving radio services, but is also advancing other branches of knowledge. It is furnishing an explanation for the variations of terrestrial magnetism, hitherto a great mystery. It supplies a way of studying various types of radiations from the sun, many of which do not reach the earth's surface because of being absorbed in the earth's atmosphere. These advances are believed to be only the beginning of gains which future exploration of the ionosphere will bring forth in abundance.

Resonant-Type Constant-Current Regulators

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Synopsis: This paper deals with the fundamentals of resonant regulators for constant current, and compares them with other kinds of regulators. It also discusses the various forms such regulators may take, their applications and control, and protective equipment required for them. A simple method of predicting performance by means of the voltage diagram is developed.

THE constant-current regulator is one piece of equipment that has been given little attention for some years. At a recent meeting of a Section of the Institute it was apparent, when the subject of constant-current regulators was mentioned, that many engineers present had only a very hazy idea of what they were. A description of the resonant type of regulator, now in its fourth decade, was received with considerable interest as an entirely fresh subject. Here, then, is a "Rip Van Winkle" who has come back to renew acquaintance with some of those other hoary oldsters that have reappeared in new clothes and increased stature. In that honorable company we find the step-type voltage regulator, the wound-core transformer, the overhead ground wire, and the spark-gap lightning arrester.

The term, constant-current regulator, as used here means a device that is used to supply a constant current to an electric system in which the receiving devices are in series, and in which the applied voltage must be varied in proportion to the impedance of the devices in use at any particular time. It is assumed that the regulation is automatic. The discussion is confined to a-c regulators.

Types of Constant-Current Regulators

A crude form of regulator can be made by inserting a large reactance in series with a number of resistance loads. The reactance consumes very little energy, but is such a large part of the total impedance that resistance loads can be connected into and out of the circuit without making large changes in the current. The fixed series reactance does not give current sufficiently constant for most purposes, and it is not widely used.

A variable reactance, either of inductance or capacity, inserted in series with the load and so designed that it automatically adjusts its reactance until the desired current flows in the circuit is the type of regulator in common use today. A new form of regulator of this type, sometimes known as a semiresonant or nonlinear network type, is one in which a saturable reactor in parallel with a capacitor of proper size behaves in the circuit like a variable capacitor, and automatically adjusts its effective reactance until a certain current flows.[1] The more common form is the moving-coil transformer that changes its leakage reactance. The moving coil is repelled from the other coil by the reaction of the currents in the windings. When properly counterbalanced, the coils will approach each other until the leakage reactance is just sufficient to pass the current for which the counterbalance weights are adjusted. In spite of the wide variance in physical form of these two regulators, they are essentially the same. Each is a variable reactance in series with the load.

The inherent characteristics of the regulators composed of a variable reactance in series with the load may be summarized for purposes of comparison as follows. The input current as well as the output current is constant. Consequently, the volt-ampere input to this type of regulator is constant and appreciably greater than the full load volt-ampere output. The power factor is comparatively low. The load circuit is reactive in character. In case of a break in it a very tenacious arc is drawn which frequently causes damage to equipment or contacts. The input circuit is also reactive in character, so switches and other control devices must be capable of breaking the reactive currents. The

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[1] For all numbered references, see list at end of paper.

losses are constant or practically so for the moving-coil regulator. The semiresonant or nonlinear network form of regulator has losses which vary about inversely as the square of the load. Consequently, the efficiency of either falls off rapidly as load is decreased below rated full load. The characteristic which is the outstanding virtue of the series impedance regulator is its independence of variations in the supply voltage. The moving-coil type of regulator has a certain amount of friction in the balancing linkages; hence it may not readjust itself for gradual voltage changes of a few per cent. Also, the inertia of the moving parts prevents rapid readjustment in case of violent fluctuations of the supply voltage. But under favorable conditions it is comparatively free from current changes caused by supply voltage change. The semiresonant regulator has no moving parts; hence it is still more free from the effects of supply voltage variation. Protective devices which de-energize the regulator in case of a break in the series circuit must be operated by the high open circuit secondary voltage, or by the lack of current in the load circuit.

A resonant network composed of linear impedances can be contrived to maintain a constant current in one element when energy is supplied at constant voltage. There are various forms that such a regulator may take, but the underlying principles are the same for all.

This resonant type of constant-current regulator differs from those previously mentioned in many important respects. It has one conspicuous fault. In fact, it is so conspicuous that it is often given weight far in excess of its importance when regulators are being chosen. This fault is that it is effected by variations in the supply voltage. The resonant regulator usually operates at the same power factor as the load. The input current is proportional to the load; hence both open circuit and overload protection are provided by an overcurrent device in the supply circuit. The load circuit is usually not reactive, and in case of a break there is practically no arcing, although film cutouts and similar devices operate perfectly. The losses vary approximately as the square of the load at the higher loads, and are approximately constant at lower loads. The efficiency is, therefore, similar to that of an ordinary transformer except that for small regulators the maximum efficiency will be near one-third load instead of three-fourths load as it is in the case of most transformers. The efficiency characteristic makes a resonant regulator especially adaptable to small regulators that do not exactly fit the load to be carried. Because there are no moving parts, adjustment to changes in load is immediate, and there are no over-shooting effects during voltage fluctuations. The high efficiency at light load makes the resonant regulator especially desirable for circuits which operate a part of the time at half load or less. The device is reversible; that is, it may be used to obtain constant voltage from a constant-current system.

The semiresonant regulator or nonlinear network type should not be confused with the resonant regulator. It employs capacitance and a *saturable-core* inductance. But the regulating function is performed in a manner analogous to the moving-coil regulator. It is essentially a variable reactance in series with the load and automatically controlled by the current. The same circle diagram that shows the performance of the moving-coil regulator will serve just as well for the semiresonant regulator. The only difference is that one uses the opposite half of the circle from the other.

Then just what is a resonant regulator? This definition may not be rigorous, but it would appear that a resonant type of regulator is a regulator that depends for the primary regulating function on one or more pairs of *linear* reactive impedances each equal to the other but of opposite sign, and which will transform from constant voltage to constant current, or from constant current to constant voltage.

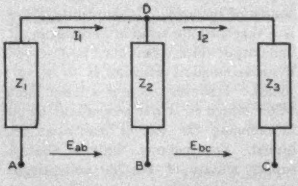

Figure 1. The general wye network

Fundamentals

The resonant constant-current regulator has been thoroughly described by Steinmetz, the inventor.[2] However, the existing literature is not of a type that permits of easy assimilation by the people who could make the most use of it. The resonant regulator is not a self-contained device, and will perform quite differently under different circumstances. For instance, it will carry more load when used on a three-phase four-wire system with neutral return than on a three-wire single-phase system. Therefore, it is essential that the men who apply this device understand how it behaves. It is also desirable that they have a convenient, simple method of predicting the performance of a given regulator under various conditions.

The resonant regulator can best be explained as a three-element wye-connected network with some special properties. A three-element network is shown in figure 1. The currents in this network are easily found in terms of the impedances involved and the applied voltages by the use of Kirchoff's laws. Solutions for the currents are as follows.

$$I_1 = [E_{ab}(Z_2 + Z_3) + E_{bc}Z_2]/[(Z_1 + Z_2) \times Z_3 + Z_1Z_2] \quad (1)$$

$$I_2 = [E_{bc}(Z_1 + Z_2) + E_{ab}Z_2]/[(Z_1 + Z_2) \times Z_3 + Z_1Z_2] \quad (2)$$

The solutions of equations 1 and 2 are general. In order that the network be a resonant regulator, it is necessary to make two of the three impedances equal and opposite, the third impedance being the load. Let us assume that Z_1 is a capacitance and that Z_2 is an inductance, and that their scalar values are equal. In that case Z_1 plus Z_2 will be zero. Therefore, the currents in the regulator and load are

$$I_1 = [E_{ab}(Z_3 + Z_2) + E_{bc}Z_2]/Z_1Z_2 \quad (3)$$

$$I_2 = E_{ab}/Z_1 \quad (4)$$

It is evident from inspection of equation 4 that I_2 is independent of the load impedance Z_3 and of voltage E_{bc}. Furthermore, the load current is always in quadrature with voltage E_{ab} and is constant as long as E_{ab} is constant.

For the purpose of understanding the operation of the regulator, the equations given are sufficiently accurate. It is, of course, not possible to have a pure inductance or a pure capacitance, but we can neglect losses for the present. The effect of losses will be discussed later.

If it is assumed that the supply voltage E_{ab} remains constant, the output current I_2 is not affected by the amount of impedance or the amount of electromotive force, of whatever origin, in the load circuit. E_{bc} can be considered as either a supply voltage or as a back electromotive force in the load circuit. While E_{bc} has no effect on the load current, it does have an effect on the input current I_1 as is clearly shown by equation 3. Note that E_{bc}, a potential introduced in the load circuit, causes a current in quadrature with it to flow as a component of I_1. Therefore, the power flowing in the supply unit *ab* may be dependent on the voltage E_{bc}, depending on the phase relation between E_{bc} and E_{ab}. These relations can best be illustrated by the voltage diagram.

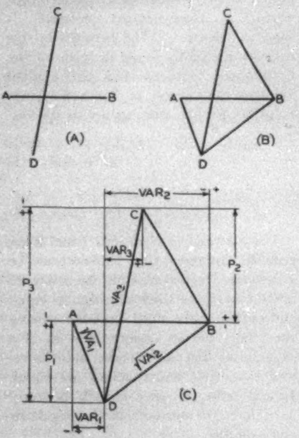

Figure 2. The voltage diagram

Subscripts 1 and 2 indicate quantities flowing in from machines *ab* and *bc*, respectively. Subscript 3 indicates quantities delivered to the load circuit

In figure 2*A* there have been drawn the lines *AB* and *CD*. The conditions imposed on their relation is that *AB* is the constant supply voltage and *CD* is the voltage drop in the load caused by a current which lags behind voltage E_{ab} by 90 degrees. If we draw lines *BD* and *AD* and *BC*, the completed diagram as shown in figure 2*B* represents all of the voltages involved in the network. Since reactances Z_1 and Z_2 are known constants and the voltage across them is shown by the diagram, and since the current in Z_2 is known and the voltage across it is shown in the diagram, the diagram completely determines the network and may be used as the basis of a chart for studying its performance.

The usefulness of the diagram will be greater if it is based on unit voltages. Assume that E_{ab} is a unit voltage, that the load current is unity, and that impedances Z_1 and Z_2 are also unity. In that case the quantities marked on the diagram are represented by the lines alongside which they appear in figure 2*C*. For convenience in discussion we will assume that voltages E_{ab} and E_{bc} are produced by machines *ab* and *bc*, respectively.

The losses can be calculated from the diagram also. The capacitor losses will be a fixed percentage of the volt-amperes flowing in the capacitor. The inductance losses will be very nearly proportional to the volt-amperes flowing in the inductance. Consequently, the diagram which shows the per cent of reactance required for any load also will show the per cent of full-load loss at any load.

The diagram clearly illustrates the effect of using a voltage *BC* such that point *C* lies well above line *AB*. In that case, machine *bc* supplies watts. At zero load these watts are all absorbed by machine *ab*. As load is added the amount absorbed by machine *ab* decreases until as point *D* reaches line *AB* it is absorbing none at all. As point *D* falls below line *AB*, the machine assumes load. Hence, when point *D* is as far below line *AB* as point *C* is above it, the machines are equally loaded.

Observe that when this condition exists and when *AB* equals *CD* that the volt-amperes of each reactance required is equal to only one-fourth of the load watts. That is the condition of load for maximum economy of material in the regulator. Note, also, that as *CD* is increased the volt-amperes of reactance required increases very nearly as the square of the load. Consequently, there is a very definite relation between input and output voltage that must be observed if an economical machine is to be obtained. However, there is a lower limit below which it is not economical to go in reducing the size of reactances required. For instance, suppose that a supply voltage of 115/230 volts single phase is available, and a load voltage of 400 volts is desired for a 6.6-ampere regulator. The load voltage is 1.74 times the supply voltage available. For a load voltage 1.74 below line *AB*, the capacitance and inductance required will be 3.53 times the load volt-amperes. However, the capacitor voltage will be 1.87 times 230 or 433 volts, and that is about as low as it pays to go for a capacitor voltage. While less volt-amperes would be required at 230 volts, the same capacity in microfarads would be required and it is more economical to provide the extra inductance than it would be to establish a 400-volt supply by a special transformer, or to build the smaller inductance and supply a current transformer of the proper ratio in the output circuit. Furthermore, it is more economical to use control equipment rated for 230-volt circuits.

The effect of an open circuit can be observed by manipulating the voltage diagram. In the case of an open circuit the load impedance becomes nearly infinite, and voltage cannot be controlled by the load impedance. Voltage tends to increase, thereby causing increases in voltages *AD* and *BD*. But *BD* is the voltage across an iron-core inductance, and this inductance will decrease in value when the voltage reaches the point at which the iron saturates. We have then a capacitor and an inductance of somewhat smaller impedance in series across voltage *AB*. Under that condition point *D* will swing far to the right of point *B*. In other words, the triangle collapses to almost a straight line. The values which voltages *AD* and *BD* assume depend on the design of the reactor, but *BD* will always be somewhat larger than normal full-load voltage, and *AD* will be approximately *AB* plus *BD*. Therefore, in the design of a regulator it is possible to limit the open-circuit voltage across the capacitor to a known value. The approximate value of *AB* plus *BD* for the open-circuit voltage means that the open-circuit voltage must be, for a single-phase regulator, something over the sum of the normal load voltage and the supply voltage. If a regulator is blindly designed for the most economical size of reactor and supply voltage for a given load, the capacitor will be subjected to rather high voltage in case of open circuit. This is another reason that we cannot always design for input and output voltages that give the most economical use of materials.

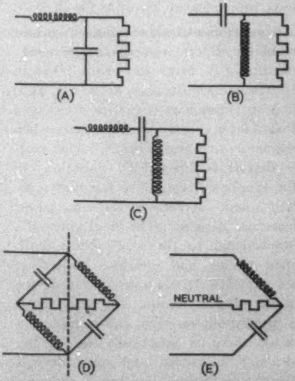

Figure 3. Some circuits used by Steinmetz

The input current under open load conditions is easily determined because both the voltage and impedance of the capacitor are known. Open-circuit protection for the regulator is obtained by setting the overcurrent device in the supply circuit to open on this current. Some such device would be required to protect the circuit in case of apparatus failure; hence no additional device is required for open-circuit protection. A very slight amount of time delay is sufficient to allow film cutouts in the series circuit to operate when a lamp burns out.

The writer has not analyzed the network sufficiently to determine the rate of rise of recovery voltage across a break in the load circuit, but numerous experiments have shown that this circuit does not tend to maintain an arc across a break in the series circuit. In fact, there is only a faint spark when the wire is broken on a regulator that has an open-circuit voltage of 1,000 volts.

The overcurrent device in the supply side is subjected to very rapid rise of recovery voltage across the switch or fusable element. The writer has used a simple "buffer" network consisting of a small capacitor (about three per cent of Z_1) and a high resistance. This network is connected across the load side of the supply fuse or circuit breaker, and is effective in reducing the recovery voltage to a point that ordinary fuses and small circuit breakers break the current without any sign of distress. The resistor also acts as a discharge resistor for Z_1 in case a break in the load circuit is followed by the opening of the supply circuit breaker.

When this buffer network is used, the duty on control equipment is light under all conditions. There is no high inrush current to lamp loads because the input current is only about one-tenth normal when the lamps are cold, and increases gradually as the filaments heat. There is no inductive arcing when the circuit is broken because the device is easily made to have a noninductive character on the supply side. There is no inrush under short circuits and grounds on the series circuit. Ordinary normal-duty contacts on time switches and relays have been found to give trouble-free service for long periods.

The regulator has no moving parts and no inertia; hence voltage surges cannot cause "pumping" or overshooting effects which will damage lamps or other equipment.

The regulator is reversible; that is, it may be used to obtain constant voltage from a constant-current circuit. This is clearly illustrated by the chart of figure 2*C*.

Losses in the inductance and capacitor have an effect on the regulation. This effect can be shown by substituting the per unit values in equation 2 to conform to the actual impedance of the reactances instead of the lossless reactances assumed previously. It would then read

$$I_2 = \frac{(m + jn)(r_1 + jx_1 + r_2 + jx_2) + (r_2 + jx_2)}{(r_1 + jx_1 + r_2 + jx_2)(r_3 + jx_3) + (r_1 + jx_1)(r_2 + jx_2)} \qquad (5)$$

This reduces with certain approximations to

$$I_2 = j[1 + (m + x_3)(x_1 + x_2) - (r_3 - n)(r_1 + r_2)] \qquad (6)$$

Remember that x_1 and x_2 are of opposite sign and very nearly equal, and that r_1 and r_2 are very small. r_1 is the equivalent per unit resistance of the capacitor, and r_2 is the equivalent per unit resistance of the inductance. They are fixed by the design of the regulator or rather of the elements of the regulator.

The quantity $(m + x_3)$ can be read from figure 2*C* on the line marked VAR_3. The quantity $(r_3 - n)$ can be read from the scale marked P_1.

It is possible to use equation 6 to work out the proper relation between r_3 and $(x_1 + x_2)$ so that I_2 remains more nearly constant for all values of r_3 than if $(x_1 + x_2)$ were always zero. The value of $(x_1 + x_2)$ can be controlled to a certain extent by proper design of the air gap in the inductance. That feature is the basis of a patent issued to S. F. Farkas in 1937. The condition necessary to perfect regulation is

$$x_1 + x_2 = (r_1 + r_2)(r_3 - n)/(m + x_3) \qquad (7)$$

Note that n will usually either be zero or one-half times the largest value of r_3 (load resistance) for which the regulator is designed. In case n is zero, very good compensation can be secured. But if n is not zero, compensation may be worse than no compensation if the regulator will ever have to carry light loads. Perhaps it would be clearer to say that it is practically impossible to design x_2 so that equation 7 will be fulfilled under the latter condition.

In some cases, however, a magnetization curve can be determined for the inductance such that the regulator will give actually constant current. For a highly efficient regulator; that is, small values of r_1 and r_2, deviations in current are quite small. For all ordinary purposes special attention to the shape of the magnetization curve is not necessary. It is sufficient to fix two points on the curve, one at or near full load, the other at or near no load. This is easily accomplished by unbalancing the regulator by means of taps on the inductance winding until no-load and full-load currents are equal.

The current may be adjusted by changing the supply voltage or by using a variable-ratio current transformer between the regulator and the load. Also, some of the special forms of regulators to be described are designed so that output current can be adjusted.

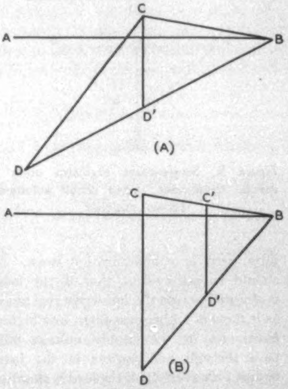

Figure 4. Voltage diagram of regulator using an autotransformer with an air gap

Practical Forms of Regulators

Steinmetz described two forms of regulators which he called the resonant T and the monocyclic square. They could be used with or without auxiliary transformers. The author has built a number of regulators which combine the functions of the regulator and the auxiliary transformers in a single device. These various forms of resonant regulators will be described. The resonant T is represented in figures 3*A* and 3*B* and by the voltage diagram of figure 2*C* provided voltage *bc* is zero. In other words, the load return wire is attached to one wire of the single-phase supply system. This is also described by saying that it consists of two equal and opposite reactances connected in series across the supply voltage with the load shunted across one of the reactances. Some may also recognize this as the familiar L

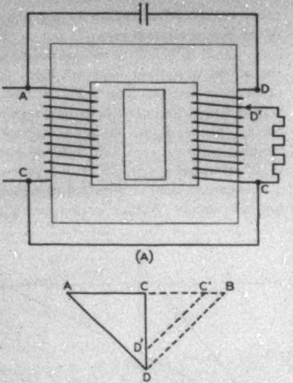

Figure 5. Single-phase regulator using a special transformer. Load circuit autotransformer coupled

filter used in communication work. It should be self-evident that if the load is shunted across the inductive reactance as is done in a high-pass filter, any higher harmonics in the supply voltage will pass through and appear in the load circuit. Conversely, if the load is shunted across the capacitor as is done in a low-pass filter, higher harmonics in the supply voltage will not pass and the current wave will be very nearly a true sine, even though the supply voltage is rich in harmonics. It is sometimes desirable for other reasons to shunt the load across the inductance. In that case harmonics may be suppressed by using an oversize capacity in series with a small inductance as the input arm of the T. This combination will be resonant at the fundamental frequency, but will not pass harmonics readily. The writer has not found any objectionable harmonics in the T-connected regulator except at less than ten per cent load.

The monocyclic square is perhaps the most familiar name for a resonant type of regulator. The connections are as shown in figure 3*D*. The symmetry of the diagram immediately suggests that it could be cut along the diagonal to which the supply voltage is applied and continue to function. Such a regulator is shown in figure 3*E*. This latter arrangement is represented by the voltage diagram, figure 2*C*, if we make voltage E_{bc} equal minus one-half of voltage E_{ab}. The advantage of the square over the half square is that it does not require a neutral wire on the supply circuit. The monocyclic square, like the resonant T with the load shunting the inductance, is affected by voltage harmonics in the supply, and can be cured by the same process as that used for the T.

Steinmetz used a back electromotive force in the load circuit equivalent to E_{bc} in our analysis. This usually consisted in the third phase of a three-phase circuit exactly as analyzed in figure 2*C*. But sometimes it was the second phase of a two-phase system introduced in the load circuit of a monocyclic square. At no load both halves of the square "folded over" so that they absorbed power. At full load the square furnished half of the power; the second phase of the system furnished the other half. This latter connection usually required that one or more auxiliary transformers be used.

The device as it has been described is about as it has existed up to the last few years. Various improvements have been made to make it more useful and flexible in its applications.

One improvement was to substitute for inductance Z_2 a transformer with an air gap in the core. In that case the transformer acts as a reactor and as a coupling transformer. This allows some leeway in the use of load voltages higher or lower than that of point *D* (figure 2). Voltage relations in such a device are shown in figure 4*A*. The current delivered from point D' is constant and equal to I_2 times the ratio BD/BD'. If the voltage diagram is not to be altered in shape (which will lower the power factor), the return current must be returned not to point *C*, but to a point C' chosen so that BC/BC' equals BD/BD'. This follows because the load current is always in quadrature with voltage E_{ab}, and to avoid pulling the voltage diagram out of shape a point for the return current must be chosen on the voltage diagram so that C' lies directly under point D' (for pure resistance loads) as it does in 4*B*. For regulators in which the ratio BD/BD' is small, there is little advantage in changing the point of current return. This is the case when a small street lighting regulator is equipped with taps near point *D* to enable the regulator current to be adjusted to the supply voltage available. But if large currents at low voltage are desired from a similar regulator, it would be essential to reduce voltage BC' in proportion to the turn ratio used to get voltage *BD*.

Realization of this essential need led to still another improvement. That was to build a special transformer such that voltage *BD* and *BC* would *both be induced in the same winding*. By that method a change of taps to get any desired turn ratio BD/BD' automatically selects a turn ratio BC/BC' that equals it. If a regulator is to be used to control current for a wide range of special tests, such as melting-time tests for fuses, this is a very valuable improvement. One method of accomplishing it is shown in figure 5, which is a single-phase regulator. Figure 5*B* is a diagram illustrating how it operates. In figure 5*B* the dotted line *CB* represents the voltage induced in coil *CD* by flux from winding *AC*. The dotted line *BD* represents the voltage induced in the same coil by the leakage flux flowing through the center leg across the air gap. Line *CD* is shown drawn parallel to the resultant voltage which will appear across coil *CD*. The load is connected across a portion of the turns of *CD*, and the coil acts as a coupling autotransformer; that is, the coil *CD* has three functions. It has induced in it part of the supply voltage. It is the reactor winding. It is a coupling autotransformer winding.

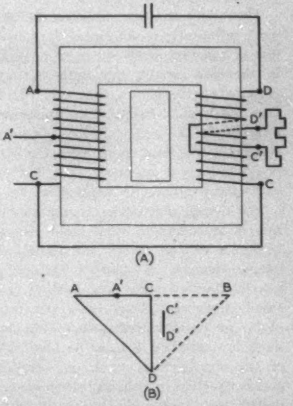

Figure 6. Single-phase regulator using a special transformer. Load circuit electrically isolated

Figure 6*A* is similar except that the windings are arranged to use a higher voltage in the resonant circuit than can be obtained from the supply available. Also, the load is coupled by using a separate winding on the same leg of the core as winding *CD*. This arrangement allows the resonant-circuit reactances to be chosen for maximum economy without regard to the supply voltage available or to the current desired. It also allows the load circuit to be insulated from the supply circuit.

Figure 7*A* is a three-phase regulator in which the transformer winding also serves a triple purpose of supply transformer, reactor, and output transformer. The diagram 7*B* shows the voltage relations. Dotted lines *BC* and *BD* are the supply and reactor components of the total voltage induced in winding *CD*.

Applications

Recent practice in series street lighting shows a trend toward smaller regulators supplying 50 to 100 lamps. During the same period there has been a trend toward higher distribution voltages. If the higher primary voltage is used to supply these regulators, high-voltage control equipment is necessary. This will mean still higher costs for constant-current regulators and control. If the number of regulators is kept low, the series circuit voltage must be high. That is not at all desirable. Many operators have turned to the multiple system for street lighting in order to keep the operating voltage low. That, too, has its disadvantages.

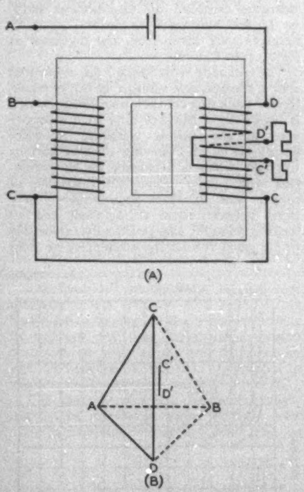

Figure 7. Three-phase regulator using a special transformer. Load circuit electrically isolated

There is a field for a low-voltage constant-current lighting regulator that is economical and can be economically controlled. If this regulator can be supplied from the lighting secondary lines instead of the primary lines, there is opened a still larger field for it, such as for airport lighting and lighting extensive private grounds. Of course, the resonant regulator can be applied at the higher voltages, but it appears to be particularly applicable at the lower voltages.

One of the most promising systems is one in which power is taken from 115/230-volt single-phase secondaries or from wye networks. The grounded-neutral grid is used as the return wire. In case of open circuit the portion of the circuit between the break and the regulator can be energized through one of the reactances at 115 volts to ground. By making a few tests with a voltmeter or test lamp, the fault is easily located. Hand control on each unit is provided so that in case of failure of one circuit the cascade can be made operative by closing the manual switch on the unit following it in the cascade. Time-switch control can be used as simply as can hand or cascade control. Any form of control that will handle sufficient power to close a relay is easily applied. Ordinary relay contacts are capable of short-circuiting a portion of the circuit for midnight lighting circuits. Figure 8 shows the current regulation and efficiency of such a regulator. If overhead wires are used, adequate lightning protection is necessary. Also, a fuse in the load circuit to protect the regulator in case of back feed from high-voltage circuits is desirable.

The resonant regulator has been applied in testing fuses for blowing time. When so used it compensates for the change of resistance of the fuse as its temperature changes. It is fast enough to hold current constant during rapid changes in the resistance. The power requirements are held down to the actual power required to fuse the link. The resonant regulator has been applied to power systems in apparatus for obtaining high-voltage direct current.[3] This application has been described in some detail in previous publications.

Production line testing, testing of motor protective devices, relays, and similar equipment are fields in which the regulator can be used. Constant-torque control for motors can be obtained from it.

The serving of single-phase loads such as electric-arc furnaces from three-phase power circuits has always been a knotty problem. The three-phase resonant regulator will supply single-phase constant current while taking its energy from a three-phase supply. The load balance is not perfect, but it will be better than is usually obtained in two-electrode furnaces. Saving in furnace construction and improved control facilities make the possibility worth investigating. Control of electrode current would be by means of the regulator. Control of furnace voltage would be by means of electrode spacing. It is believed that independent control of these two quantities would be quite valuable in some processes.

Resonant regulators can no doubt be applied in many fields. They are not an expensive device to build. However, the profession seems to have forgotten them; or perhaps it has never been really acquainted. If this effort serves to bring them to mind when a possible application is discovered, its purpose will be fulfilled.

List of Symbols

E_{ab} = the principal applied voltage
E_{bc} = the second applied voltage
I_1 = current flowing in the capacitance
I_2 = the output current of the regulator
Z_1 = the impedance of the capacitor
Z_2 = the impedance of the inductance
Z_3 = the load impedance
$m + jn$ = the components of the unit voltage E_{bc}/E_{ab}
$r_1 + jx_1$ = components of the unit impedance Z_1/E_{ab}
$r_2 + jx_2$ = components of the unit impedance Z_2/E_{ab}
$r_3 + jx_3$ = components of the unit impedance Z_3/E_{ab}
P_1 = power supplied by source of voltage E_{ab}

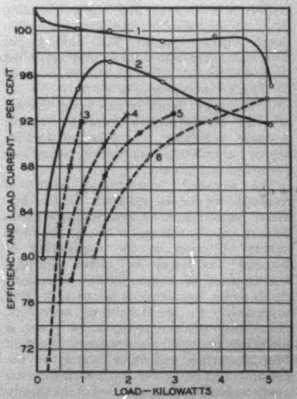

Figure 8. Regulation and efficiency curves

1—Current from a four-kva resonant regulator

2—Efficiency of the same regulator

3, 4, 5, 6—Efficiency curves for one-, two-, three-, and five-kva moving-coil regulators

P_2 = power supplied by source of voltage E_{bc}
P_3 = power absorbed by load
VAR_1 = reactive volt-amperes supplied by source of voltage E_{ab}
VAR_2 = reactive volt-amperes supplied by source of voltage E_{bc}
VAR_3 = reactive volt-amperes absorbed by load

References

1. A Static Constant-Current Circuit, C. M. Summers. AIEE Transactions, 1938, pages 636–9.

2. Theory and Calculation of Electrical Circuits (a book), Charles Proteus Steinmetz. McGraw-Hill Book Company, first edition pages 245–96.

3. Constant-Current D-C Transmission, C. H. Willis, B. D. Bedford, and F. R. Elder. AIEE Transactions 1935, pages 102–08.

Discussion

J. Peterson (nonmember; General Electric Company, West Lynn, Mass.): Mr. Miner has presented an interesting review of the fundamentals of resonant regulators for constant current. We feel sure that his concise and yet comprehensive presentation of the characteristics of these resonant circuits will revive interest in their applications by the profession in general.

An obvious reaction to Mr. Miner's paper is the question, why have moving coil regulators been used almost exclusively for series street lighting during the last four decades while the virtues of resonant regulators have apparently gone unheeded all these years?

The truth of the matter is, that resonant regulators have undergone considerable development by various manufacturers of street-lighting equipment during these decades, in an effort to utilize the desirable properties of these circuits, and at the same time, to minimize or eliminate the undesirable characteristics. This work began with Steinmetz who applied and improved the fundamental circuit which was invented by Boucherot in France in 1890.

Development work is still being carried on, but in its present form the simple resonant regulator is not a satisfactory device for universal application to modern street-lighting circuits.

The so-called "conspicuous fault" of resonant regulators referred to by Mr. Miner (variations in load current with variations in supply voltage) is by far the most serious objection to the application of resonant regulators in street lighting. Maintenance of lumen output with long life in series incandescent lamps is of vital importance to street-lighting operators. Close limits of current regulation (plus or minus one per cent) are necessary to obtain these properties, and unfortunately, in the resonant regulator, the current regulation is only as good as the regulation of the supply voltage. Usually it is necessary to allow for considerable variation of primary supply voltage in the distribution circuits from which series street-lighting equipment is energized.

We grant that starting surges are present in the automatic types of moving-coil regulators, but on the other hand, the regulator design minimizes these surges and furthermore the design of series incandescent lamps takes into account these surges and life is, therefore, not adversely affected.

The presence of harmonics in resonant regulator circuits has always been a source of difficulty in applications to series lighting. Mr. Miner has pointed out that certain resonant circuits pass harmonic distortion in the primary supply on through to the load circuit. It is obvious, of course, that these same circuits encourage harmonic distortion in the load-circuit current, when nonlinear load elements exist. Autotransformers and insulating transformers with burned-out lamps on their secondaries generate harmonic distortion on open circuit, which, in the case of the monocyclic square, for instance, causes the root-mean-square series current to *increase dangerously* above the normal value.

The increasing use of vapor lighting in series circuits further precludes the use of simple resonant regulators. Both sodium- and mercury-vapor lamps have arc characteristics which promote distortion in both current and voltage wave forms in resonant circuits. When stabilized by inductive reactance as in moving-coil regulators, the current through the lamps remains practically sinusoidal and distortion appears in the voltage alone. Harmonics in the current must be avoided because both life and lumen output are dependent to a great extent on the use of sine-wave current through the lamp.

Another difficulty introduced by harmonics in the series-circuit current wave shape is telephone interference, particularly from long single-wire loops. Fortunately, the almost universal use of moving-coil regulators has minimized this type of difficulty on both incandescent- and vapor-lamp series lighting circuits.

I would like to stress the distinction between the functions of open-circuit protective equipment for resonant regulators as opposed to moving-coil regulators. Protective equipment is absolutely essential to protect the resonant regulator itself from destruction due to resonance currents within the machine when the load is open circuited. On the other hand, this protection equipment when used with a moving-coil regulator is not required to protect the regulator itself, but rather to protect the load circuit external to the regulator. As a matter of fact, the protective equipment is optional in the latter case and many moving-coil-regulated circuits are operating today without protective equipment.

An interesting characteristic of the polyphase resonant networks not stressed by Mr. Miner, is the fact that the terminals of three-phase equipment must be connected to the three-phase lines in a definite phase sequence depending on the phase rotation of the polyphase lines.

A study of a resonant regulator manufactured in a practical form reveals some interesting points. There will be required a series of taps in the reactors and transformer elements. One group of these taps is necessary to permit the manufacturer to compensate for manufacturing variations in capacitance values in the capacitor section. The other group of taps is necessary to permit the customer to adjust the machine for the actual line voltage that exists on the customer's property. When an insulating load transformer has been added to the simple resonant regulator and when suitable filter equipment for the elimination of harmonics in the load circuit has been added, the kilovolt-amperes of equipment required is such that the economics are favorable to the moving-coil regulator even when the moving-coil regulator is provided with power-factor-correcting capacitors.

W. A. Wolfe (Kansas Gas and Electric Company, Wichita): Mr. Miner is to be congratulated for renewing the acquaintanceship of the profession with the resonant-type of constant-current regulator, and for developing a regulator of this type which is practical for commercial use.

Mr. Miner mentions that the resonant regulator has been used for testing fuses for blowing time. I have used one of the regulators built by Mr. Miner with very successful results for fuse testing. The regulator used was 6.6-ampere four kilovolt-ampere for series-street-lighting service and designed for a 230/115-volt supply source. In the use I made of it the regulator demonstrated its ability to carry considerable overload on intermittent duty. In the fuse-blowing tests currents up to 30 amperes were taken from the regulator at loads up to 15 kva.

The company with which I am associated uses a considerable number of 66-kv transformer-bank fuses of their own design, which is essentially a Micarta tube with a copper wire as the fusible element. Accurate knowledge of the blowing time of various size fuse wires is necessary for co-ordination with relays. Since the resistance of copper wire increases approximately five times between room temperature and its melting point, it was practically impossible to get good results by attempting to hold

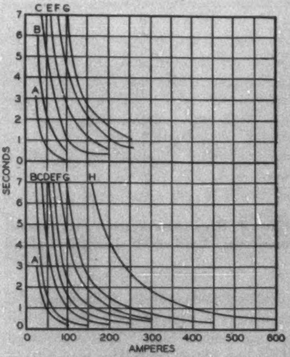

Figure 1

A—Number 26 copper
B—Number 24 copper
C—Number 22 copper
D—Number 21 copper
E—Number 20 copper
F—Number 19 copper
G—Number 18 copper
H—Number 16 copper

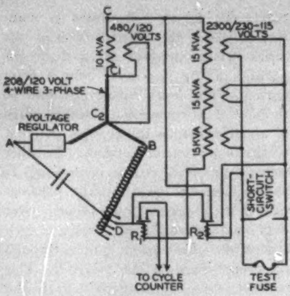

Figure 2

the current through the fuse constant by means of a hand-controlled rheostat of any kind.

Using the resonant constant-current regulator in conjunction with a current transformer and an induction regulator to get the desired values of current, it was possible to get very consistent results.

In figure 1 of this discussion the top group of curves were made using a hand-controlled water rheostat while the bottom group was obtained by the use of the resonant regulator. The improvement is pronounced, as the top group of curves is obviously inconsistent.

Figure 2 of this discussion shows the diagram of the connections used to obtain a current through the fuse in the 400- to 600-ampere range. The diagram is drawn so that the supply voltage and the elements of the regulator form a voltage diagram as well. The letters *A*, *B*, *C*, and *D* designate the same relative points as in Mr. Miner's paper.

The load on the regulator for different values of fuse current was kept within limits by changing connections or cutting in and out the three 15-kva distribution transformers used as current transformers and by moving the point *C* connection to any one of the three positions *C*, C_1, or C_2.

The function of relay, R_2, was to short-circuit the regulator when the fuse blew thus preventing excessive voltage rise on the regulator and excessive current from the supply circuit.

Roland R. Miner: Mr. Peterson's observation that the simple resonant regulator is not satisfactory for *universal* application to modern street-lighting circuits is of course correct. Use of a resonant regulator requires that consideration be given to application problems as well as to the regulator proper.

However the almost exclusive use of moving-coil regulators for the past 40 years does not prove that resonant regulators do not have enormous possibilities. Our series-street-lighting practices have been built around the moving regulator. Had they been built around a resonant regulator the practices and applications would not have been the same.

The lack of development of this type of regulator is in the writers opinion largely the result of commercial considerations and engineering development at the time Steinmetz's work was done. Consider that there was no efficient core material for reactors. Capacitors were very expensive, bulky, and not very dependable. The resonant regulator lacked the inherent inductance necessary to stabilize the arc lamps in common use. Furthermore few users would have been able to understand and properly apply the regulator. Later when the conditions had changed, the profession was busy at other things and the old patents which might once have helped justify further development had expired.

As to the maintenance of proper supply voltage to provide good current regulation, that also is an application problem. The writer has not found it difficult. It should be pointed out that most voltage variations occur when series circuits are not operating. Consequently the regulation obtained during the hours of darkness is all that needs to be considered.

The effect of nonlinear elements in the series circuit is outside of the writers experience. However, analysis indicates that if the harmonic content of the voltage wave in the load circuit is not over about 50 per cent and if the wave forms of all of the devices are similar it does not appear to be impossible to use a resonant regulator, *provided it is adjusted on the wave form on which it is to be used*. A mixture of linear and nonlinear loads would lead to difficulties.

The question of current surges reducing lamp life is not one of starting surges. Starting surges occur when the lamps are cold and are probably harmless. The surges which take a toll of lamps are the ones which occur when a considerable portion of a loaded circuit is short-circuited while the lamps are burning and the ones which are caused by system disturbances. This is especially important if the regulator is lightly loaded.

Comparison of costs of resonant regulators versus moving-coil regulators is largely one of design and of course depends on the purpose for which the regulator is designed. Whether filter equipment to correct for defects in wave form of certain types of lamps is justly chargeable to the regulator is questionable. The series transformer can be eliminated as shown in the paper. Taps, at least on small regulators, have not offered any difficulties or any great expense. The simplicity of control and the lower first cost of small units are two factors that have contributed savings of well over 20 per cent on two installations now in use. These installations have performed more satisfactorily than the ones they replaced.

In order to use the resonant regulator effectively for series street lighting it is necessary to consider the whole system including the lamps, the type of distribution system, the optimum size of units, and a number of purely operating features. While many circuits now supplied with moving-coil regulators could be supplied with resonant regulators of the same rating it would not be economical in part of the cases. In general small units appear to be the most favorable from the standpoint of cost. Some circuits now served by large regulators and operated at high voltage could be cut into smaller segments and operated at lower voltage. Some circuits now using 20-ampere lamps with insulating transformers could be operated without insulating transformers by using a few small 20-ampere regulators fed from low-voltage networks. It certainly would not be safe to assume that the two types of regulators are interchangeable in an existing system. Each should be considered only for the work it is particularly fitted to perform.

An Automatic Voltage Regulator Without Moving Parts Employing Ferroresonance

PALMER H. CRAIG
FELLOW AIEE

Synopsis: An automatic line voltage regulator is described which employs ferroresonance and operates without tubes or moving parts of any kind. The device requires no maintenance attention nor expense, is highly efficient, very accurate, and much faster in its response than previous large-size line regulators.

DESIRABLE features in a line-voltage regulator either for substation or central-station service or for industrial service covering applications such as those requiring a constant alternating voltage for test conditions should, obviously, include as many as possible of the following:

1. No moving parts
2. Complete freedom from maintenance attention or expense
3. A high over-all efficiency
4. No appreciable distortion of the wave form
5. Rapid response
6. Economy in initial cost and maintenance

A regulator incorporating all of the above features has been on the commercial market for several years for loads of the order of a few kilovolt-amperes.[1] Recently, the sizes in which this regulator is being built have been extended into the higher power field up to a load of 625 kva.

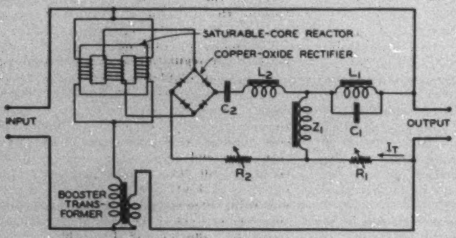

Figure 1. Basic wiring diagram of the voltage regulator

All of these regulators with which the author has worked employ a circuit of which figure 1 is a simplified diagram. The heart of the operation of this circuit depends upon the ferroresonant networks utilized. The reactors L_1 and L_2 in figure 1 are iron-core devices operated on the knee of their saturation curve in such a manner that for a slight change of applied voltage across these reactors there will be a slight change of flux in their cores. Due to the portion of the characteristic curve on which they are worked, this change of flux will change the apparent inductance of the coil throwing it either into or out of resonance with the associated capacitor at the frequency of the impressed voltage. We see from figure 2 that as the impressed voltage decreases slightly from normal, the current through L_1 decreases very rapidly. L_1 and C_1 are associated as a parallel resonant circuit and their output can be thought of as feeding the autotransformer Z_1. Consequently, a slight decrease in the line voltage from normal will increase the output from Z_1 and will impress a higher voltage on the series resonant circuit comprised of the reactor L_2 and capacity C_2. Figure 2 illustrates the manner in which the current through the series circuit increases for a slight departure of the impressed voltage from normal. The series circuit L_2C_2 can be thought of as comprising a second stage of amplification of the changes inherent in the first resonant network. In other words, the series circuit comprising L_2 and C_2 increases the sensitivity of the entire control circuit tremendously over that obtained from a single stage of such a network. The current I_2 flows through the copper-oxide-rectifier bridge R_2. This rectifier supplies direct current to the d-c saturating leg of a saturable-core reactor. Saturable reactors are too well known to require further description but it will suffice to say that an increased direct current in the middle leg of this device will decrease the impedance of the a-c coils wound on the outer two legs. These a-c coils are placed in series with the primary of a booster transformer, the secondary of which is in series with the line. The a-c coils are, of course, so poled as to produce no induced electromotive force in the middle leg, a shorted turn or coil usually being used on the

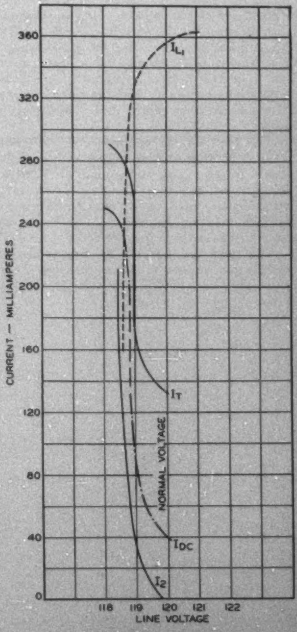

Figure 2. Variation of current in the control circuit with line voltage

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The author wishes to acknowledge the valuable work of Lester C. Herman, of the Invex Corporation, in developing this regulator, and of Doctor Benjamin L. Snavely, of Lehigh University, for his assistance in the preparation of the mathematical analysis.

[1] For all numbered references, see list at end of paper.

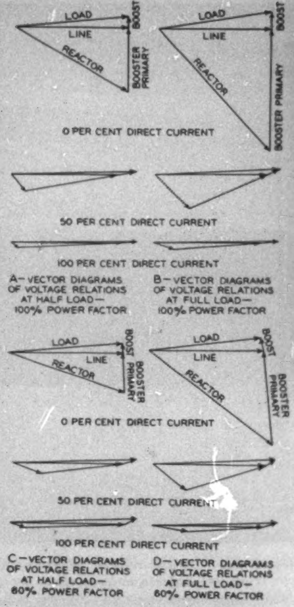

LOAD
LINE
REACTOR
BOOST
BOOSTER PRIMARY
0 PER CENT DIRECT CURRENT
50 PER CENT DIRECT CURRENT
100 PER CENT DIRECT CURRENT
A—VECTOR DIAGRAMS OF VOLTAGE RELATIONS AT HALF LOAD—100% POWER FACTOR
B—VECTOR DIAGRAMS OF VOLTAGE RELATIONS AT FULL LOAD—100% POWER FACTOR
C—VECTOR DIAGRAMS OF VOLTAGE RELATIONS AT HALF LOAD—60% POWER FACTOR
D—VECTOR DIAGRAMS OF VOLTAGE RELATIONS AT FULL LOAD—60% POWER FACTOR

Figure 3. Vector relationships between line, load, reactor, and booster voltages

Figure 4. Oscillograms of voltage and current relationships. Input voltage varying

middle leg to insure that no a-c flux will exist in that leg. The a-c coils may be connected in series or parallel with each other as required.

It should be noted that no part of the load current flows through any of the resonant circuits, which is important because the saturating currents introduce wave-form distortion in the current flowing through them. Since this current is rectified and used only for saturation in the regulators being described, the resonant networks introduce no wave-form distortion in the load circuit. Note, for example, the output voltage wave form of figures 4 and 5.

Since the lowest output available from the control circuit is never zero, a constant "bucking" winding is also used on the center leg of the saturable-core reactor. This coil is supplied with just enough direct current to oppose completely the variable saturation at the condition of highest normal line voltage, thus producing no net saturation at that condition.

Summarizing, as the output voltage of the regulator tends to decrease slightly from normal there will be a very rapid increase in the d-c saturation of the saturable reactor and a relatively large boost introduced by the booster transformer of an amount just sufficient to offset the tendency of the line voltage to decrease.

It should be noted that the added boost is obtained not merely due to a higher voltage on the primary of the booster transformer but because of a shift in position of the vectors of the voltages across the a-c coils of the reactor, primary and secondary of the booster transformer, and the line voltage.

Figure 3 illustrates the manner in which these vectors change for two load conditions at unity power factor and similar conditions at 60 per cent power factor. It can be easily seen from these vector diagrams that the magnitude of the booster primary voltage is not nearly as important as its vector relationship with respect to the line-voltage vector. It is also apparent from figure 3 how buck may be obtained in the line comprising the booster transformer without changing any of the connections of that trans-

Table I. Data Taken on Regulator for 25-Kva Load

Number of Test	E In	E Out	I_L In	I_L Out	Kilovolt-Amperes In	Kilovolt-Amperes Out	I_s	Kilowatts Out	I^2R Loss in Shunt Circuit	Control Circuit Watts	Power Factor of Load
1	2,380	2,376	more than 10 amperes	10			0.9	24.3	30.5	70	1
	2,200	2,376		10		23.76	0.95	24.0	34	210	1
	2,180	2,376		9.8		23.2	0.96	23.7	34.8	220	1
2	2,440	2,380	7.8	7.35	19	17.5	0.72	15.0	19.6	70	0.86
	2,200	2,376	9	7.35	19.8	17.45	0.95	15.25	33.9	210	0.874
3	2,410	2,380	more than 10 amperes	9.25		22	1.27	12	75.5	70	0.55
	2,200	2,360		9.13		21.55	2.35	12	20.8	210	0.55
4	2,480	2,380	6.3	5.98	15.6	14.24	0.6	10.2	13.6	70	0.72
	2,300	2,330	6.85	5.78	15.7	13.5	1.18	9.8	52.7	100	0.73
	2,160	2,340	7.65	5.78	16.55	13.55	1.9	10.2	135.5	210	0.75
5	2,440	2,360	6.1	5.58	14.88	13.19	0.66	9.2	16.5	70	0.7
	2,260	2,340	6.8	5.52	15.35	12.8	1.34	9.05	68	120	0.71
	2,170	2,340	7.4	5.52	16.05	12.8	1.9	9.1	136	210	0.71
6	2,180	2,360	7.5		16.35		1.9	8.35	136	210	

former. For example, referring to figures 3*C* and 3*D*, under the condition of zero direct current in the reactor we see that the position of the "boost" vector is such with respect to the line-voltage vector as to produce an output voltage lower than the line voltage.

The oscillograms of figures 4 and 5 will give some idea of the currents and voltages which exist in the various parts of the circuit of figure 1.

In figure 4, trace number 1 represents the output voltage, number 2 the total current of the control circuit, number 3 the current through L_1, number 4 the current through C_1, number 5 the current through the series resonant circuit, and number 6 the d-c output to the reactor. It can be seen that the wave form of the load voltage is not appreciably distorted under any condition. The variation in the oscillogram was obtained by producing arbitrarily a system voltage drop which produced the condition shown therein.

Figure 5 is a similar oscillogram wherein the variation was caused by an input voltage drop due to impressing the load on the output of the regulator.

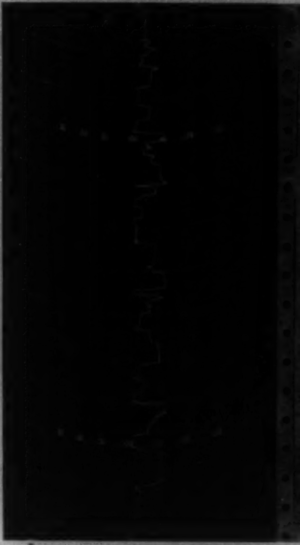


Figure 6A. Typical input voltage variation used for test

Figure 6B. Output voltage under input conditions shown in figure 6A

Efficiency

Table I gives test data on a typical regulator for 25-kva 2,400-volt load in which the input and output voltages are given as well as the input and output currents, kilovolt-amperes, shunt current (that is, the current through the a-c coils of the reactor and the primary of the booster transformer), kilowatts out, I^2R losses, control-circuit losses, and power factor of the load. This table shows an over-all accuracy under all conditions of a total of about 2.1 per cent or an accuracy of plus or minus 1.05 per cent. As seen from the table, the efficiency is very high and it should be noted that the power factor of the load is varied from 0.55 to unity, which is a larger variation than would normally be encountered.

Accuracy of Regulation

While the accuracy shown in table I is only approximately plus or minus one per cent, it is quite easy to obtain an accuracy very much better than this figure. Numerous commercial installations of the smaller-sized regulators have been made in which the accuracy is held to within plus or minus one-quarter of one per cent. The author does not wish to imply that an accuracy of this magnitude can be maintained under all conditions, but for special test applications where extremely high accuracies are required and where the conditions of application of the regulator are well known, the device can be quite easily adjusted to accuracies of this order of magnitude.

Figures 6*A* and 6*B* represent respectively the input and output voltages on a system regulated by this regulator, where the input was varied manually.

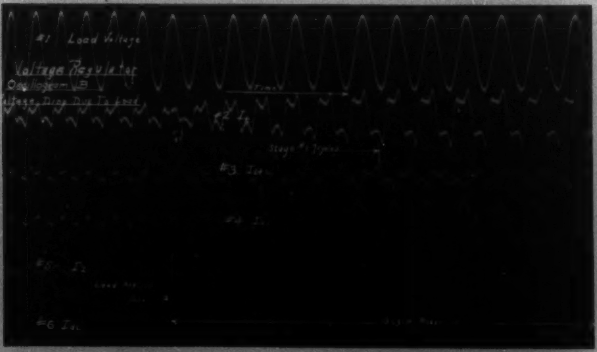


Figure 5. Oscillograms of voltage and current relationships. Load varying

Variation of the Magnitude and Power Factor of the Load

Figure 6*C* illustrates the effect of varying both the magnitude and power factor of the load through very wide limits. For a certain design of a regulator, full load at 60 per cent power factor produced a range of regulation from approximately $2^3/_4$ per cent buck to 10 per cent boost. The same regulator for half load at 60 per cent power factor covered a range of from about $^3/_4$ per cent boost to about $11^1/_4$ per cent boost. At unity power

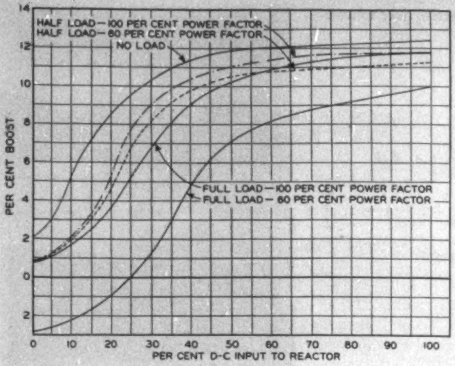


Figure 6C. Range of regulation with various loads

factor the half-load range was from about $^{3}/_{4}$ per cent boost to about $11^{3}/_{4}$ per cent boost. For the no-load condition, the range was from about $2^{1}/_{8}$ per cent boost to about $12^{1}/_{2}$ per cent boost. In other words, under the worst possible change of power factor and load for this design, a range from about 2 per cent boost to 10 per cent boost would have been realized. Since the time of that design, improvements have been made in the regulator so that in some models a net over-all range under the worst possible conditions of some 15 per cent is obtained. Obviously, by special design a greater range could also be covered.

Speed of Response

Figures 7*A* and 7*B* illustrate respectively the condition where the input voltage drop is due to impressing the load, and the condition wherein the load is kept constant and the input voltage is decreased. In figure 7*A* it is apparent that the output voltage is completely restored to normal in four cycles. In figure 7*B* it can be seen that the output voltage is restored in approximately eight cycles. In the worst possible condition wherein the input voltage is varied by as much as ten per cent or more all in one step and instantaneously, the output voltage is restored to normal in approximately 14 cycles. The difference between the above time constants can be explained as follows.

Referring to figure 1, when the drop in input voltage is due to an increased load, we see that there will be an increased current produced in the primary of the booster transformer when the increased load is impressed. This increased current is in the right direction to produce increased boost in that transformer. On the other hand, when the load is kept constant and the input voltage is decreased, this decrease in input voltage tends to decrease the current in the primary of the booster transformer which is in the wrong direction for regulation, thus the control circuit in this case must restore the booster primary current not only to normal but increase it in the opposite direction, that is, it must reverse the direction of change of this current and then carry it to whatever increased value is necessary for regulation. This obviously requires a longer time than in the first case.

Figures 7A and 7B. Oscillograms of input and output voltages

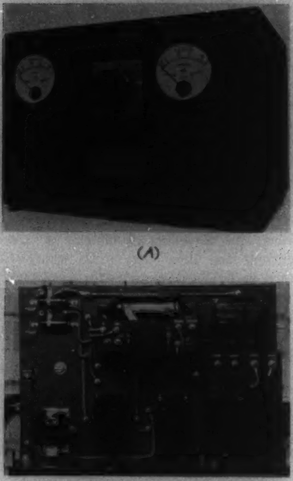
Load varied in figure 7*A*. Input voltage varied in figure 7*B*

Physical Arrangement of Various Sizes

Figures 8*A*, 8*B*, and 8*C* illustrate an exterior and two interior views of the regulator in sizes to handle 1- and 2.5-kva loads. Figure 9 illustrates the arrangement for loads of 5, $7^{1}/_{2}$, 10 and 25 kva. Figure 10 shows a 30-kva three-phase unit and figure 11 shows the interior of the transformer portion of this size regulator. This three-phase unit is essentially three single-phase regulators each supplied with its own control circuit so that any type of unbalanced load may be regulated perfectly on every phase. The three units shown at the bottom of figure 11 are the saturable-core reactors, those on the top are the booster transformers, and those in the middle are tapped autotransformers for shifting the range of regulation up and down the scale as desired. In the small-size units, the later effect is accomplished by simply rotating the knob on the front of the panel which controls a small variable autotransformer to provide any desired

Figure 7*A*

Figure 7*B*



(A)

(B)

Figures 8A and 8B. Exterior and interior views respectively of regulator for 2.5-kva load

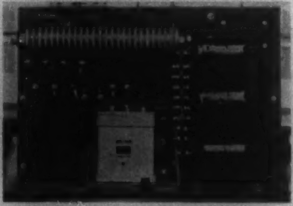


Figure 8C. Rear of interior of 2.5-kva regulator

output voltage and to maintain that voltage constant after it has been set at the required place.

Analysis of Series Resonant Circuit

Figure 12 illustrates the notations utilized in the following mathematical analysis.

Assume that the reactance of the iron-cored reactor can be expressed in the form:

$$X_{ls} = \lambda_s - b_s E_l \qquad (1)$$

λ_s and b_s are constants

E_l = applied voltage
$E_l = |e_l|$

Bold face letters will refer to the vector values of current and voltage. Corresponding upper-case letters refer to absolute values.

$$E_l = X_{ls}I = \lambda_s I - b_s E_l I$$

$$\therefore E_l = \frac{\lambda_s I}{1 + b_s I}$$

$$E_s = E_l - E_c = \frac{\lambda_s I}{1 + b_s I} - X_{cs}I$$

$$= \frac{\lambda_s}{b_s} - X_{cs}I - \frac{\lambda_s}{b_s}\left[\frac{1}{b_s I} - \left(\frac{1}{b_s I}\right)^2 + \dots\right]$$

Let I_c be such that $E_s = 0$
Then

$$I_c = \frac{\lambda_s}{X_{cs}b_s}$$

if we neglect terms $\frac{1}{b_s I}$ etc.

$$\therefore E_s \approx (I_c - I)X_{cs} \qquad (2)$$

Analysis of Parallel Resonant Circuit

Assume that:

$$X_{lp} = \lambda_p - b_p E_p \qquad (3)$$

where λ_p and b_p are constants.

$$I = I_c - I_l = \frac{E_p}{X_{cp}} - \frac{E_p}{X_{lp}}$$

$$= \frac{\lambda_p - b_p E_p - X_{cp}}{X_{cp}(\lambda_p - b_p E_p)} E_p$$

or

$$b_p E_p^2 + (X_{cp} - \lambda_p - X_{cp}b_p I)E_p + X_{cp}\lambda_p I = 0$$

Let E_c be such that $I = 0$
then

$$\lambda_p = X_{cp} + b_p E_c$$

$$\therefore b_p E_p^2 + (-b_p E_c - X_{cp}b_p I)E_p + X_{cp} \times (X_{cp} + b_p E_c)I = 0$$

$$E_p = \frac{1}{2}\left\{E_c + X_{cp}I \pm (E_c - X_{cp}I) \times \left[1 - \frac{4X_{cp}^2 I}{2b_p E_c^2}\left(1 - \frac{X_{cp}I}{E_c} + \dots\right)^2\right]^{1/2}\right\}$$

If

$$\frac{X_{cp}I}{E_c} << 1 \text{ and } \frac{X_{cp}}{b_p E_c} << 1$$

$$E_p \approx \frac{1}{2}\left\{E_c + X_{cp}I \pm (E_c - X_{cp}I)\left(1 - \frac{2X_{cp}^2 I}{b_p E_c^2}\right)\right\}$$

Upon discarding the negative sign:

$$E_p \approx E_c - \frac{X_{cp}^2 I}{b_p E_c} \qquad (4)$$

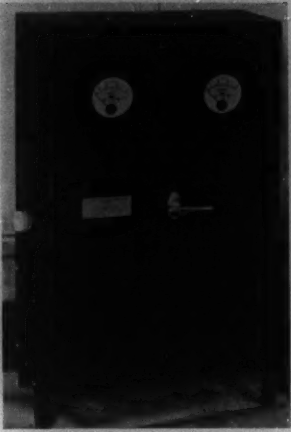


Figure 9. Exterior view of regulator for loads of 5, 2.5, and 10 kva

Combined Series and Parallel Resonant Circuits

Assume that $E_p > E_s$; that is that the regulating circuit draws a leading current.

$$E_0 = [(E_p - E_s)^2 + (RI)^2]^{1/2}$$

In order that the regulating circuit may be effective, that is that a decrease in current in the circuit shall correspond to an increase in E_0, R must certainly

Figure 10A. Regulator for 30-kva three-phase load

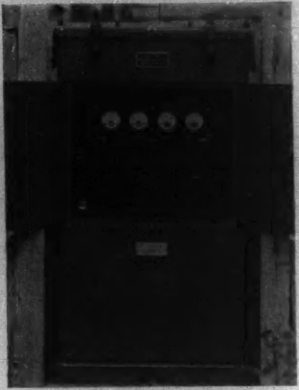


Figure 10B. Interior of control portion of 30-kva three-phase regulator

be smaller than that given by the equality $RI = E_p - E_s$. Hence

$$E_0 \approx E_p - E_s$$

$$= E_c - \frac{X_{cp}^2 I}{b_p E_c} - (I_c - I)X_{cs}$$

$$\therefore I \approx \frac{E_c - I_c X_{cs} - E_0}{\dfrac{X_{cp}^2}{b_p E_c} - X_{cs}} \tag{5}$$

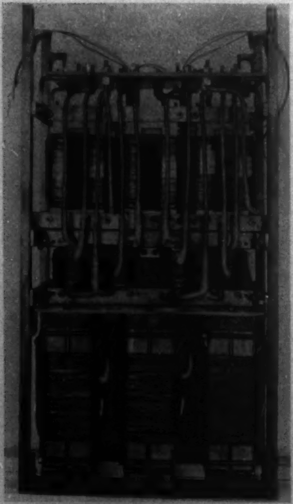


Figure 11. Transformer portion of 30-kva regulator

Let

$$E_c - I_c X_{cs} = V \text{ and } \frac{X_{cp}^2}{b_p E_c} - X_{cs} = r$$

then

$$I = \frac{V - E_0}{r} \tag{5a}$$

Power Circuit

Let k = ratio of primary turns to secondary turns on the transformer.

Let X_1 = reactance of transformer primary when secondary is open. Then we must have:

$$\left.\begin{aligned} \mathbf{E}_1 &= \mathbf{E}_r + \mathbf{E}_p \\ \mathbf{E}_0 &= \mathbf{E}_l + \mathbf{E}_2 \\ \mathbf{E}_1 &= k\mathbf{E}_2 = jX_1\left(\mathbf{I}_1 - \frac{\mathbf{I}_0}{k}\right) \\ j &= \sqrt{-1} \end{aligned}\right\} \tag{6}$$

Also we may write:

$$\begin{array}{lll} \mathbf{E}_0 = E_0 & & E_0 \text{ is real} \\ \mathbf{I}_0 = I_0(\cos\theta + j\sin\theta) & & I_0 \text{ is real} \\ \mathbf{I}_1 = I_1(\cos\phi + j\sin\phi) & & I_1 \text{ is real} \\ \theta = \text{angle of lead for the load} & & \\ \phi = \text{phase angle to be determined} & & \end{array}$$

We shall assume that the a-c resistance of the d-c controlled reactor may be neglected. Thus in addition to the relations given above:

$$\operatorname{Arg} \mathbf{E}_r = \operatorname{Arg} \mathbf{I}_1 + \frac{\pi}{2} \tag{7}$$

Combining the above relations:

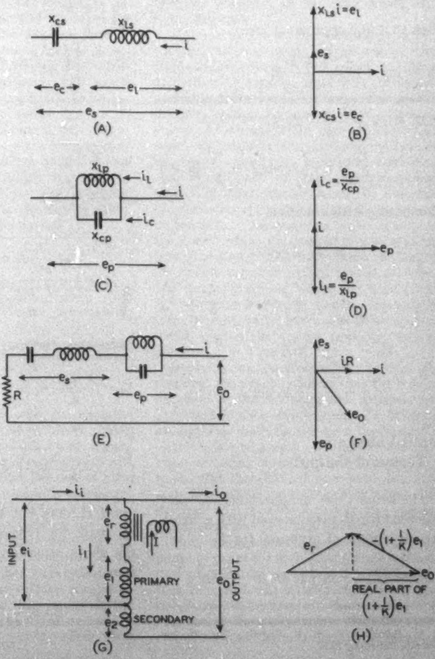
$$\begin{aligned} \mathbf{E}_r = \mathbf{E}_0 - \left(1 + \frac{1}{k}\right)\mathbf{E}_1 = \mathbf{E}_0 - {} \\ \left(1 + \frac{1}{k}\right)jX_1\left(\mathbf{I}_1 - \frac{\mathbf{I}_0}{k}\right) \\ = E_0 + \left(1 + \frac{1}{k}\right)X_1\left(I_1\sin\phi - \frac{I_0}{k}\sin\theta\right) - {} \\ j\left(1 + \frac{1}{k}\right)X_1\left(I_1\cos\phi - \frac{I_0}{k}\cos\theta\right) \end{aligned} \tag{8}$$

$$\begin{aligned} \mathbf{E}_l = \mathbf{E}_0 - \frac{1}{k}\mathbf{E}_1 \\ = E_0 + \frac{1}{k}X_1\left(I_1\sin\phi - \frac{I_0}{k}\sin\theta\right) - {} \\ j\,\frac{1}{k}X_1\left(I_1\cos\phi - \frac{I_0}{k}\cos\theta\right) \end{aligned} \tag{9}$$

Determination of ϕ

By virtue of (7) (using the notation of ordinary vector analysis):

$$\mathbf{E}_r \cdot \mathbf{I}_1 = 0$$



x_{cs}
x_{ls}
i
e_c
e_l
e_s
(A)
$x_{ls}i = e_l$
e_s
i
$x_{cs}i = e_c$
(B)
x_{lp}
i_L
i
i_c
x_{cp}
e_p
(C)
$i_c = \frac{e_p}{x_{cp}}$
i
e_p
$i_L = \frac{e_p}{x_{lp}}$
(D)
i
e_s
R
e_p
e_0
(E)
e_s
iR
i
e_0
e_p
(F)
i_i
i_0
INPUT
e_i
e_r
i_1
I
e_1
PRIMARY
e_0
OUTPUT
e_2
SECONDARY
(G)
e_r
$-\left(1+\frac{1}{K}\right)e_1$
e_0
REAL PART OF
$\left(1+\frac{1}{K}\right)e_1$
(H)

Figure 12. Illustrating the notations employed in the mathematical analysis

$$\left[E_0-\left(1+\frac{1}{k}\right)jX_1\left(I_1-\frac{I_0}{k}\right)\right]\cdot I_1 = E_0\cdot I_1+\left(1+\frac{1}{k}\right)\frac{1}{k}X_1(jI_0)\cdot I_1=0$$

$$E_0I_1\cos\phi+\frac{1+k}{k^2}X_1I_0I_1(\cos\theta\sin\phi-\cos\phi\sin\theta)=0$$

$$\therefore \tan\phi=\frac{\sin\theta-\dfrac{k^2E_0}{(1+k)X_1I_0}}{\cos\theta} \qquad (10)$$

Determination of I_1

Let us assume that the drop across the d-c controlled reactor can be expressed accurately enough for present purposes in the form

$$E_r=\frac{\rho I_1-\beta}{I} \qquad (11)^*$$

where ρ and β are positive constants.

(The question of the value of E_r in the neighborhood of points where $I=0$ need not concern us since the current supplied by the resonant network will never become zero.)

If

$$E_1<\frac{1}{2}E_0$$

then to a fair approximation:

$$E_r=E_0-(R\rho)\frac{1+k}{k}E_1$$

$$\therefore E_r\approx E_0+\frac{1+k}{k}X_1\times\left(I_1\sin\phi-\frac{I_0}{k}\sin\theta\right)$$

Combining with equation 11

$$\frac{\rho I_1-\beta}{I}=E_0+\frac{1+k}{k}X_1\times\left(I_1\sin\phi-\frac{I_0}{k}\sin\theta\right)$$

$$\therefore I_1=\frac{E_0-\dfrac{1+k}{k^2}X_1I_0\sin\theta+\dfrac{\beta}{I}}{\dfrac{\rho}{I}-\dfrac{1+k}{k}X_1\sin\phi} \qquad (12)$$

Input Voltage in Terms of Output

The same type of approximation that was used for E_r may be used with a much greater degree of accuracy for E_i.

$$\therefore E_i\approx E_0+\frac{1}{k}X_1\left(I_1\sin\phi-\frac{I_0}{k}\sin\theta\right)$$

in which I_1 is obtained from equation 12 and ϕ is obtained from equation 10, and the I occurring in equation 12 is to be obtained from equation 5*a*.

$$E_i=E_0+\frac{1}{k}X_1\left[\frac{\left(E_0-\dfrac{1+k}{k^2}X_1I_0\sin\theta\right)(V-E_0)+\beta r}{\rho r-\dfrac{1+k}{k}X_1\sin\phi(V-E_0)}\times\sin\phi-\frac{I_0}{k}\sin\theta\right] \qquad (13)$$

Expression for Output Voltage

Neglecting foi the present the involvement of E_0 in $\sin\phi$, equation 13 may be regarded as an equation of the second degree which may be solved for E_0. Equation 13 may be written:

$$E_0^2-\left[\frac{1+k}{k}E_i+V-\frac{\rho r}{X_1\sin\phi}\right]E_0-\frac{\rho r}{X_1\sin\phi}\left(\frac{I_0X_1}{k^2}\sin\theta+E_1\right)+\frac{1+k}{k}VE_i+\frac{\beta r}{k}=0$$

$$\therefore 2E_0=\frac{1+k}{k}E_i+V-\frac{\rho r}{X_1\sin\phi}\pm\sqrt{\left(\frac{1+k}{k}E_i+V-\frac{\rho r}{X_1\sin\phi}\right)^2+4\left[\left(\frac{I_0X_1}{k^2}\sin\theta+E_1\right)\frac{\rho r}{X_1\sin\phi}-\frac{1+k}{k}VE_i-\frac{\beta r}{k}\right]}$$

$$=\frac{1+k}{k}E_i+V-\frac{\rho r}{X_1\sin\phi}\pm\left(\frac{1+k}{k}E_i-V+\frac{\rho r}{X_1\sin\phi}\right)\times\sqrt{1+4\frac{\rho I_1\dfrac{X_1}{k^2}\sin\theta-\dfrac{\rho E_i}{k}-\dfrac{\beta X_1}{k}\sin\phi}{\dfrac{1+k}{k}E_i-V+\dfrac{\rho r}{X_1\sin\phi}}r}$$

Discarding the root:

$$E_0\approx\frac{1+k}{k}E_i-\frac{\dfrac{1}{k}\rho I_0X_1\sin\theta-\rho E_i-\beta X_1\sin\phi}{\left(V-\dfrac{1+k}{k}E_i\right)X\sin\phi-\rho r}\times\frac{r}{k} \qquad (14)$$

Since E_0 does not differ greatly from E_i we may, for purpose of substituting in the above equation, replace E_0 in equation 10 by E_i.

$$\therefore \tan\phi\approx\frac{\sin\theta-\dfrac{k^2E_i}{(1+k)X_1I_0}}{\cos\theta} \qquad (15)$$

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United States Patent to P. H. Craig: Number 2,138,732.

Discussion

W. Richter (A. O. Smith Corporation, Milwaukee, Wis.): The usual voltage regulator employing a saturable reactor and capacitor has a rather poor wave shape on the output side. This is no serious drawback, if the regulator is to be used for the regulation of devices where the root-mean-square value only is of importance, such as for instance the filaments of thermionic tubes, but this distortion of wave shape will materially affect the regulation, if for instance the peak value is of importance; such a case would arise for instance if the regulated voltage were rectified and then used for the operation of *X*-ray or similar tubes. While a root-mean-square meter connected across the output voltage may show a constant value in spite of variations of the input voltage, a d-c meter connected across the rectified voltage would show considerable variation if serious distortion occurs.

It would seem that this undesirable distortion should be quite less with the device described by Mr. Craig, due to the fact that he does not regulate the whole voltage, so to speak, but simply adds a small booster voltage in series with the line voltage. This has the additional advantage that the load current does not flow through the whole regulated voltage. Since the actual regulated voltage is only a small part of the total voltage any distortion occurring in this small part will distort the total voltage to a considerably smaller degree.

It would have been of interest if the paper would have given some information as to the effect of small frequency variations on the regulated voltage.

C. Lynn (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Several years ago the Westinghouse Electric and Manufacturing Company experimented with a regulator using saturable cores for controlling the voltage regulation. Thermionic tubes were used for rectifiers and by the use of two saturable cores, both boost and buck to the same extent could be obtained. Instead of using a ferroresonant network for a voltage sensitive element in the control, the equivalent was obtained by means of a bridge employing resistors having different temperature-resistance coefficients. The voltage variation of this voltage-sensitive bridge element was applied to the grid of a thermionic tube to control the saturating current, thus giving quite accurate and close voltage regulation both for buck and boost.

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* For applications of this formula see the paper by C. V. Aggers and W. E. Pakala, *The Electric Journal*, February 1937.

This development work was abandoned, however, because of the poor operating performance, especially efficiency, and because of its large size in comparison to a conventional induction voltage regulator for the amount of power regulated.

Referring to the vector diagrams in Mr. Craig's paper, it should be noted that the reactor voltage and the booster primary voltage are quite large, even greater than that of the line voltage. Thus for the 25-kva load, the booster transformer is larger than 2.5 kva for ten per cent range of voltage regulation and the saturable-core reactor is even still larger.

In the data in table I on this type of regulator, the control circuit loss and the I^2R loss in the shunt circuits alone are as much as 345 watts. When to this is added the I^2R loss in the secondary of the booster transformer, the core loss of the booster transformer, and the much larger core loss of the saturable-core reactor, steps must, of course, be taken to maintain the total losses to a sufficiently low value to make this apparatus competitive.

For a comparable 25-kva load using a conventional induction regulator, for the same total, ten per cent voltage range, only a $1^{1}/_{4}$-kva unit would be used giving five per cent boost and five per cent buck. This $1^{1}/_{4}$-kva regulator has a total loss, including the average loss of the control device and its motor (note that the control device only consumes power during the short interval when it is actually changing the voltage with no power required to hold a different voltage) of about one-half of the watts loss of the control circuit alone, of the regulator described by Mr. Craig.

For small amounts of power there is still another type of voltage regulator available in capacities up to two kilowatts. This is the saturated-core capacitor type of regulator, also using no moving parts, nor even a rectifier or any separate control devices. This device will deliver output voltage constant within plus or minus one per cent or even better with a primary voltage varying 30 per cent total, that is, ±15 per cent. This device is particularly suited for supplying power for use with electronic devices and similar application. It has poor efficiency and large reactive kilovolt-ampere loss due to its having to handle the entire amount of power being controlled instead of only the portion being regulated, and is relatively large for the amount of power controlled. Thus this type is not comparable in this respect to any of the saturable-core reactor-type voltage regulators.

Paul H. Odessey (Heyer Products Company, Belleville, N. J.): Doctor Craig's analysis of the ferroresonant circuit used in this regulator employs concepts that are commonly associated with linear resonance conditions, but which appear to be of limited value regarding the type of phenomena under examination. While this method of approach may have certain practical advantages, the resulting interpretation of combined ferroresonant elements is restricted to rather idealized approximations. In this respect, the treatment is somewhat obscure concerning the physical aspects of such circuits.

The behavior of simple ferroresonant circuits, as is well known, is characterized by double-valued properties which in transition are unstable and subject to abrupt changes in value. Under limiting conditions, however, such circuits exhibit characteristics that are both single valued and sensitive to slight variations (critical stable conditions).

In this application, the use of a complex ferroresonant circuit that would have multi-valued characteristics appears to be objectionable because of the existence of several unstable conditions. Likewise, it is possible that the circuit may operate over a portion of its characteristic ineffective to the regulator. In circuits of this kind, this situation may well arise during switching operations.[1] It is likely, therefore, that the ferroresonant elements combined in Doctor Craig's control circuit have single-valued characteristics and operate possibly under so-called critical stable conditions.

In any case, the conditions under which the control circuit performs as a single-valued sensitive element do not appear to be correlated with analysis. The foundation of Doctor Craig's treatment is based upon the assumption that unity power factor (or more explicitly, the condition of equal and opposite reactive components) sufficiently determines the sensitive operating condition. In previous work,[2] however, critical conditions defining the sensitive character of ferroresonance and based upon circuit stability, were found to be independent of unity power factor.

Doctor Craig's application of ferroresonance in a regulator system is commendable for as the performance indicates, an unusual degree of regulation is attained. The control circuit employed in this system is unique and exhibits properties that should bear further investigation.

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Palmer H. Craig: The voltage regulator described in this paper is, of course, quite different from that described by C. Lynn. Mr. Lynn states that development work was abandoned on his regulator because of poor operating performance, especially efficiency, and because of large size. When it is borne in mind that regarding operating performance, the voltage regulator described in the present paper has an accuracy far better in its commercial form than that obtainable from the best induction voltage regulator, at a speed of response very much faster than could be possible with any induction voltage regulator, it would seem that operating performance is definitely better from those standpoints. Efficiency was not considered to be a major point in connection with the relatively small size regulators described in the present paper, which are used commercially, chiefly in testing and laboratory applications. In such applications efficiency is a very minor point. In the large-size regulators we have improved the efficiency to a point where it compares very favorably with the induction voltage regulator. Data in this regard will be presented in a future paper dealing primarily with the larger size regulator.

It is true, as Mr. Lynn points out, that the kilovolt-ampere parts size of the booster and reactor utilized in the present voltage regulator is larger than the actual percentage regulation obtained. The physical size of the saturable-core reactor utilized in this regulator is about $1^{1}/_{2}$ times the kilovolt-ampere parts size of an equivalent transformer showing a ratio to load represented by the percentage regulation. Compared with the advantages of the present regulator, however, it is not felt that this added physical size is a serious handicap.

Referring to the last paragraph of Mr. Lynn's discussion, it is hardly felt that the regulator Mr. Lynn mentions is comparable with the regulator described in this paper, since the two are designed to cover quite different fields of load, and since no part of the load circuit flows through the resonant network in the case of the present regulator. The regulator described in this paper does not produce an appreciable distortion of wave form nor introduce a large reactive kilovolt-ampere loss in the line, nor exhibit the poor efficiency of the type which Mr. Lynn discusses.

With reference to the discussion of W. Richter, an important advantage of the regulator described in this paper has been pointed out, namely, that very little appreciable distortion in the wave form occurs in the present regulator. Mr. Richter points out several of the many instances in which an undistorted, regulated voltage is necessary. Similarly, in testing any iron-core device such as fractional-horsepower motors or small transformers, the presence of harmonics in the regulated voltage is very undesirable. Variations in the frequency of the line to which the present regulator is attached of a magnitude such as is experienced on ordinary public utility power systems, will not appreciably effect the regulation. If, however, frequency departs materially from normal, variations in the point around which regulation occurs will be noticeable.

Replying to the discussion by Paul H. Odessey, the author realizes that the results obtained in the mathematical analysis are restricted in their application. In devising an algebraic analysis of even a fairly simple circuit it is necessary to choose between solutions involving certain simplifying assumptions, and therefore of restricted validity, and more elaborate solutions in which the primary effects of variation in the various parameters are difficult to follow.

No attempt has been made in the present paper to prove the stability or single-valuedness of the solution obtained. While it is true that a simple series ferroresonant circuit possesses multivalued characteristics, it does not follow necessarily that the more complex circuit treated here is multivalued

Recent Developments in Generator Voltage Regulation

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Synopsis: This paper discusses the fundamental requirements for stability in a generator voltage regulating system having several time delays. A new rheostatic type of voltage regulator element is described, together with a method of introducing antihunting means into the regulating system. In the appendices, a mathematical treatment gives the requirements for stability and adequate damping for several typical voltage regulating systems. It is shown that with certain systems, theoretically perfect regulation and also high damping are possible.

ALL voltage regulators are in effect amplifiers because small deviations in the regulated voltage are made to produce relatively large changes in the generated voltage of the final machine to offset the internal voltage drop caused by variations in load. Recently, conventional electronic tubes have been used as amplifiers in such regulating systems.[1] A little analysis will show that all previous voltage regulators have also been amplifiers, although this concept has not been used to denote their performance characteristic. Such devices as vibrating contacts, saturable reactors,[2] and motor-operated rheostats[3] have been used to produce the large changes in excitation for small errors in the regulated voltage and although in some cases their action has been intermittent in character, the net result produced has been amplification.

In this paper, it will be assumed that the output voltage of the amplifier is continuously variable and is proportional to the deviation voltage at the input. This assumption represents very closely the net characteristic of all such amplifiers, even those using vibrating contacts, because the vibration effect rarely appears in the output voltage of the machine being regulated. Such a concept greatly simplifies the solution of complicated systems because all of the relations over a limited range may be assumed to be linear.

Application of the above assumptions to practical regulating systems has shown that the calculated stability and damping characteristics check very closely the actual performances of such systems. This is a distinct advantage as compared with "cut and try" methods used in the past.

The theoretically perfect regulating system has infinite amplification. Certain systems which will be described in the body of the paper would permit the use of infinite amplification with stability and good damping provided an amplifier with infinite amplification were available. In practice, it is possible to devise systems using any of the above mentioned types of amplifier for very high amplification and accuracy, the only practical limitations being mechanical friction, magnetic hysteresis, etc. This is at variance with the thought that accuracy is incompatible with stability.

New Regulator Element

In order to make the discussion of these problems more concrete, a description of a new form of regulator element will first be given. Following this, the methods of obtaining stability of regulators in general and the new regulator in particular, will be shown.

The regulator, known as the "Silverstat," consists of a novel rheostatic control member, requiring very small force and movement, arranged to vary a resistor having a large number of steps. Figures 1 and 2 show the arrangement.

A number of silver buttons are so mounted that they may be actuated in sequence by a driving member. Each button is carried on the free end of a flat leaf spring which normally rests against a block of insulating material. The leaves are clamped together as shown with insulation between them. The buttons are separated from each other when the driving member is at the left-hand end of its travel. A small movement to the right, only a small fraction of an inch, is required to close the gaps between all of the buttons in sequence. Since each leaf spring is connected to a tap on the regulating resistance, the sequential closing or opening of the buttons respectively short-circuits or cuts in portions of the resistance. The insulating block serves to give the springs a

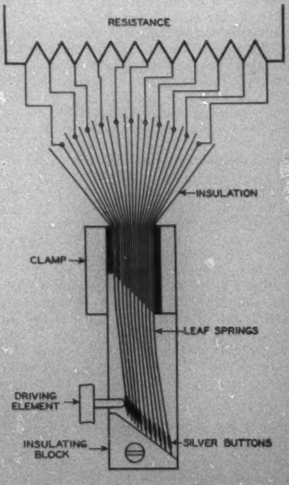

Figure 1. Schematic of Silverstat

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[1] For all numbered references, see list at end of paper.

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in its response to the application of an arbitrary constant electromotive force. As a matter of fact, it may be shown by a three dimensional graphical analysis (a method which is sufficiently general that it permits account to be taken of the nonlinear nature of the reactor and rectifier resistances) that throughout a wide range of choice of circuit constants, the sensitive circuit will have a single-valued response for all values of applied voltage, quite apart from any reference to the so-called critical stable conditions.

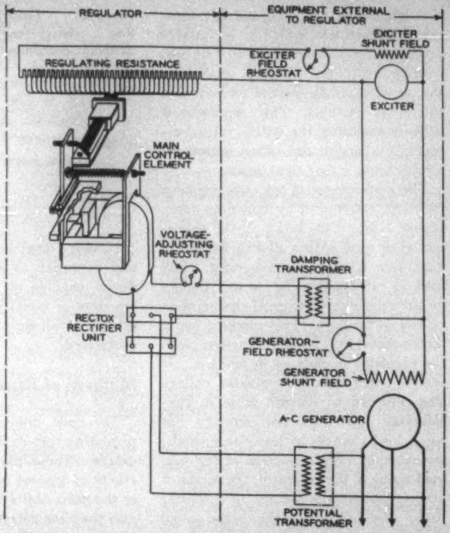
While it may be desirable to operate the circuit with approximately equal and opposite reactive components, such a condition is by no means necessary for the functioning of the circuit. The discussion of unity power factor is therefore entirely irrelevant and especially so since the reference which Mr. Odessey gives concerns a very different circuit from the present one.

definite initial loading which insures a fixed minimum pressure between each pair of buttons before the next pair is shorted, and to space the buttons uniformly regardless of the initial straightness of the leaves. Turning the block through a small angle provides a simple adjustment by means of which the button spacing may be changed.

Figure 3 shows the complete voltage regulator with cover removed. The tapped resistor is placed in the ventilated compartment at the rear, and the Silverstat control member in an enclosed projection near the top. The driving element, mounted just below, is of the moving iron type. It consists of a C-shaped iron magnetic circuit and a potential coil, with an iron armature arranged to move in the constant air gap of the magnetic circuit. The arm which carries the armature comprises the single main moving portion of the regulating device. This arm is mounted on leaf-type springs arranged at right angles to each other, thus providing a frictionless type of axis without wearing parts about which the moving arm is free to turn within the required limits of travel.

When the potential coil is energized, the armature is attracted into the air gap of the magnetic circuit. The use of a constant air gap tends to minimize any change in force due to position. The magnetic pull on the armature is balanced by a coiled spring attached to the arm and located just above the magnetic circuit. Thus at normal voltage on the potential coil, the movable system is in equilibrium.

Figure 4. Circuit for regulator system



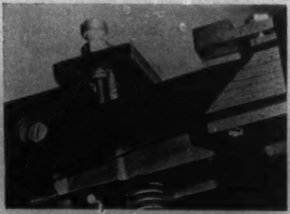


Figure 2. Rheostatic control member

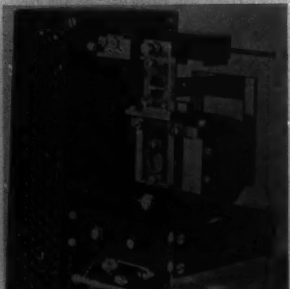


Figure 3. Silverstat voltage regulator

The voltage of an a-c generator may be controlled as shown by the schematic diagram of figure 4. The generator field is energized by an exciter. Potential for the d-c coil of the voltage regulator is obtained by means of a suitable potential transformer and a dry-type full-wave rectifier.

The action of the Silverstat regulator in controlling the a-c generator voltage will be readily understood by reference to the schematic diagram and the following description. Assume that the a-c machine and exciter are brought up to normal speed and voltage under regulator control. When the voltage on the regulator coil is below normal, the pull of the main spring on the moving element is greater than that of the electromagnet, and therefore, the main spring holds the driving member against the silver buttons, maintaining them closed, thus short-circuiting the regulating resistance. The buttons remain closed up to the moment when the alternating voltage approaches the normal value. When this takes place, the pull of the electromagnet on the moving-iron armature overcomes the opposing pull of the main spring and the driving member backs off, thus opening the silver buttons in sequence to cut resistance into the circuit of the exciter shunt field. The regulator moving element takes a position where just sufficient steps of the regulating resistance are short-circuited to give the excitation required for normal a-c generator voltage.

The damping transformer shown in figure 4 is for the purpose of eliminating hunting. Its action will be described in greater detail under the heading "Methods of Securing Stability."

The regulating resistance has sufficient steps so that the voltage change per step in the normal working range is small, and therefore, smooth voltage control is achieved. The regulating action is that of a semistatic device which operates only when a correction in voltage is necessary.

Due to the fact that the voltage per step is kept below the arcing value, and the volt-amperes per step within reasonable limits, there is no serious pitting of the silver buttons by the short-circuiting or cutting in steps of resistance. By reason of simple construction, and the selection of suitable materials and ratings, the life of the device is practically unlimited.

The use of a separate regulating resistance permits flexibility in the choice of the total resistance and the resistance per step, which may be varied to suit the requirements of the machine and type of service for which the machine is used.

The location of the resistance in a separate compartment where it is suitably protected from external injury and adequately ventilated, removes heat from the vicinity of the control element and the silver buttons. This arrangement permits enclosing the entire voltage-responsive element and silver button assembly under a dust-tight cover.

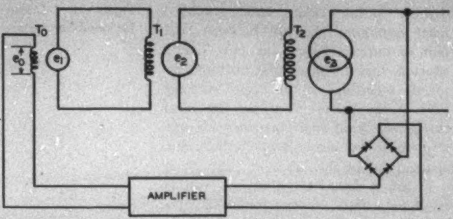
The performance of the new regulator has been determined by numerous tests. Figure 5 shows the action of the regulator when used with a 25-kva 2,300-volt 1,200-rpm 60-cycle a-c generator. Full load at rated power factor was thrown on the generator by manual closing of an oil circuit breaker. This machine had a direct-connected 125-volt exciter, with the regulator circuits as in figure 4. It will be noted that the regulated voltage was returned to normal value in considerably less than one second. For usual load changes of lesser magnitude, for example, only a fraction of the full-load rating of the generator, the regulator acts to correct the voltage in a shorter time. For different machines, the actual time required for correction of voltage after a load change will vary, depending on the machine time constants.

The satisfactory damping action of the regulator should be noted. There was no oscillation of the regulated voltage during its recovery to the normal value.

In order to meet the requirements of portable and marine applications, the regulator moving arm is statically balanced. For this reason the regulator will operate satisfactorily at various angles of tilt from the vertical. It may be even laid on its back, face, or side without causing wide changes in the regulated voltage.

Figure 5. Oscillogram showing application of full load to a 25-kva 2,300-volt 1,200-rpm 60-cycle a-c generator

Figure 6. Three time delays—no damping transformers



Having described the construction and operation of a suitable amplifying device capable of handling fairly large amounts of excitation power, the methods of obtaining stability will next be considered.

Methods of Securing Stability

The chief difficulty in stabilizing all regulating systems is the presence of time delays. These may be the time constants of various inductive circuits such as the fields of the rotating machines and also the time delays involved in the amplifier itself. The latter may be electrical, mechanical, or both. In power-generation systems, the usual circuit consists of a voltage regulator and two rotating machines, the exciter and the generator whose voltage is to be regulated. Any delay in the amplifier in addition to the delays in the field circuits of the two rotating machines makes a total of three delays. The circuit shown in figure 6 idealizes such a system by showing the amplifier without delay, but with an extra exciter to represent its delay so that all the constants can be represented by simple inductive and resistive electrical circuits.

With this circuit, the only possibility of obtaining stability is to use low amplification as shown in appendix II where a computation is made for: $T_0 = 0.2$ second, $T_1 = 1$ second, $T_2 = 5$ seconds. It is shown that the amplification may not be greater than 37 if the system is to be free from hunting and that it must be considerably lower than this value in order to result in adequate damping for reasonably rapid recovery from an oscillating condition following a disturbance caused by a change in load. A particular case is computed assuming amplification of 13, for which the rate of decay is 74 per cent per cycle.

A much more satisfactory method of stabilizing voltage-regulator systems is to introduce into the input of the amplifier one or more voltages which are proportional to the rates of change of the various machine voltages. Such voltages may be obtained by various combinations of resistance with capacitors, reactors, or mutual inductances. The choice will depend largely upon the input characteristic of the amplifier. In the present case with the magnetically driven Silverstat regulator, the mutual inductance or damping transformer is a suitable method. The circuit of figure 7 will be used to give a physical understanding of the action of such transformers. Assume a suddenly applied voltage e_0 to the field of the rotating machine. It will be shown that a voltage immediately appears at the secondary terminals of the transformer and that for a certain relation between transformer constants and field constants this voltage will equal e_0. At the start, the inductance of the field circuit will be the principal factor determining the current and

$$e_0 = Lpi_0$$

$$i_0 = \frac{e_0}{Lp}$$

where p is the time derivative operator.

In most d-c machines, the generator voltage and field voltage are approximately equal and small changes in field voltage produce approximately equal changes in generator voltage after sufficient time has elapsed for the field current to build up. The change in generator voltage will at that time equal the change in i_0R of the field and for inter-

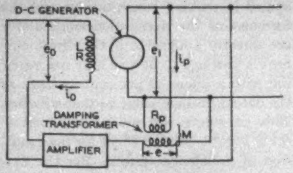


Figure 7. Antihunting stimulus introduced by damping transformer

vening values of i_0 during its growth, i_0R also represents the intervening values of the change in generator voltage. Therefore,

$$e_1 = i_0R = \frac{e_0R}{Lp} = \frac{e_0}{Tp}$$

where

$$T = \frac{L}{R}$$

The transformer is designed to have sufficient resistance in its primary circuit as compared with its inductive reactance to cause the primary current to rise and fall approximately in phase with the applied voltage. With this in mind, the induced voltage in the secondary of the transformer is,

$$e = Mpi_p = Mp\frac{e_1}{R_p} = tpe_1 = \frac{t}{T}e_0$$

Thus, if the time constant $t(= M/R_p)$ of the transformer is equal to the time constant T of the field of the rotating machine, there will be induced instantaneously in the secondary of the transformer a voltage equal to the impressed voltage at the field terminals. Such a feed-back voltage when properly connected to the input of amplifier in a direction to oppose the change in the input which caused e_0 to appear in the output will, of course, be a powerful antihunting influence.

The foregoing may be stated in words as follows: A suddenly applied voltage e_0 produces a rate of change of current in the field winding, which in turn causes the generated voltage to rise with a definite rate. This rising voltage applied to the mutual inductance produces a rising current in the primary which (neglecting inductance) has a proportional rate. Induced in the secondary is a definite voltage equal to the mutual inductance times the rate of change of primary current. Thus an antihunting voltage e proportional to and in phase with e_0 appears at the input of the amplifier.

This does not give any quantitative determination of the antihunting properties of such transformers, but merely illustrates the physical nature of their action. In what follows, several systems employing damping transformers will be described and their performance shown.

The circuit of figure 8, for example, shows a system with three time delays and with three damping transformers. Here again the delay in the first exciter may be thought of as representing the delay in the regulator element or amplifier. It is shown in appendix I that if

$$t_1 = T_0$$
$$t_2 = T_1$$
$$t_3 = T_2$$

the regulator system is more than critically damped; the solution for the recovery of e_3 following any disturbance being of the form

$$e_3 = A\epsilon^{-\frac{t}{T_0}} + B\epsilon^{-\frac{t}{T_1}} + C\epsilon^{-\frac{t}{T_2}}$$

It is seen that no damped oscillatory term is present and that the rate of recovery is determined principally by the largest of the time delays which is usually T_2.

This solution is true for the above choice of damping transformers no matter how large the amplification. Thus a perfect regulating system with more than adequate damping is theoretically possible.

In practice, a transformer t_3 having a time constant comparable with that of the final circuit T_2 would be quite large. Fortunately, the transformer at that position can be omitted because it is still possible to obtain adequate damping of the system by virtue of the other transformers. The circuit shown in figure 9 is the same as the one described, but with t_3 omitted. In appendix III, the damping is computed for the same time delays as indicated in the description of the circuit shown in figure 6; namely,

$$T_0 = 0.2 \text{ second}$$
$$T_1 = 1 \text{ second}$$
$$T_2 = 5 \text{ seconds}$$

In this appendix, t_1 is chosen equal to 0.2 second and t_2 equal to one second. The solution shows the system to be oscillatory, but so highly damped that the decay for one cycle of its oscillation amounts to 74 per cent. This damping is obtained with infinite amplification and, therefore, the system may be theoretically perfect in its regulating ability.

In the corresponding circuit without damping transformers as computed in appendix II, it was necessary to reduce the amplification to 13 in order to obtain an equivalent degree of damping of free oscillation.

The calculations in appendix III show the order of time constants required for damping transformers in a regulating system which is highly damped and yet which has infinite amplification. If a lower degree of damping is desired the time constants of the damping transformers may be reduced. A simple, practical method of reducing and controlling the time constant of a given damping transformer is to use a small adjustable resistance in series with the primary winding. For a given choice of transformers, the damping may be increased by lowering the amplification.

Experimental results with regulating systems as described above show that the calculated performance of the systems checks very closely the actual performance. As many as four machines, a generator, and three exciters, have been set up experimentally in a practical regulating system. With damping transformers to offset the various time delays, satisfactory performance was secured. In fact, such a system might be extended

Figure 8. Three time delays with three damping transformers

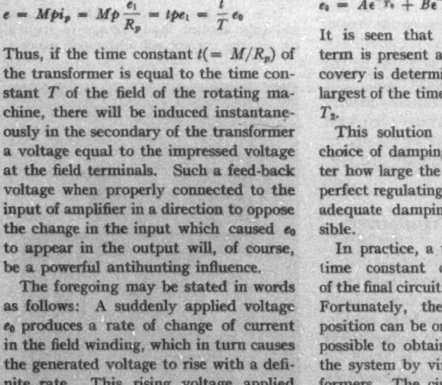
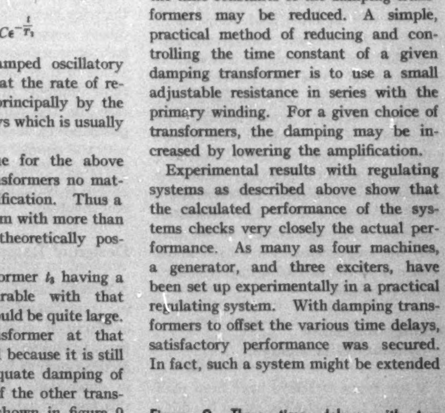


Figure 9. Three time delays with two damping transformers



indefinitely as indicated by the relations in appendix I.

In another application, two exciters with a single pair of regulating contacts operating in the field of the first exciter were used to regulate a 4,300-horsepower synchronous motor operating as a generator. The damping transformers for this installation were calculated in advance from the time constants of the machines and when installed, the regulator performed as predicted by the calculations. The sudden application of approximately full load to the system showed the regulator to be stable, and very highly damped. The regulated voltage changed about one-half of one per cent with the above load change showing that the contacts were giving high amplification. By using several exciters in cascade as above, the current in the field of the exciter may be made very small so that the power handling requirements of the regulator element are reduced. The use of several cascaded machines does not appreciably reduce the rate of recovery, because the exciters are rapid as compared to the generator. Equation 16 of appendix I shows that only the longer time delays have much influence on the rate of voltage recovery of the generator.

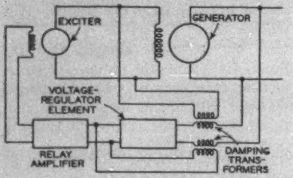


Figure 10. Voltage regulator with relay amplifier

Voltage Regulator Systems With Relays

Many types of relays have been used in the past to increase the power handling capacity of voltage regulators. In all such systems, a sensitive element responding to the small deviations in the regulated voltage delivers its output to the relay or amplifier which in turn controls the excitation of the first rotating machine. The circuit of figure 10 shows the arrangement schematically with the addition of damping transformers for obtaining stability. Two such transformers are shown. If the regulator element and the relay amplifier both have considerable time delay, an additional transformer with primary connected across the output of the amplifier might be necessary. In many cases, however, both the piloting element and the amplifier are sufficiently rapid in their performance that the circuit may readily be stabilized using only the transformer with primary connected across the exciter.

Figure 11 shows a relay employing the Silverstat principle, capable of controlling larger amounts of field power. It is made up of four components similar to those previously described in the direct-driven element. The several elements may be connected in various ways, depending upon the current and voltage requirements. For parallel connection, a small resistance which cannot be short-circuited by the Silverstat buttons is placed in series with each branch. The relay is adjusted mechanically to cause all sections to be short-circuited approximately together, the series resistance causing approximate equality in the division of current for possible errors in the mechanical adjustment.

One pilot element is readily capable of controlling two or more relay amplifier Silverstats to increase the power to any value that may be needed. In such cases, the relay elements have their output terminals connected in series so that any lack of synchronism between the movements of their mechanical parts will not cause improper division as would be the case for the parallel connection. The power rating, of course, increases directly with the number of such relays provided the proper choice of resistance per step or button is made for the voltage and current involved.

Design of Damping Transformers

With the usual connection of the damping transformers in the regulator circuits as described, direct current flows in both primary and secondary windings with directions such as to produce ampere-turns in opposition. Advantage is taken of this fact by balancing the ampere-turns for the average value of the exciter voltages so that as large a value of mutual inductance as possible may be obtained with a given size. The relatively large variation in the exciter voltage from this mean value, however, necessitates the introduction of an air gap in the core to give best results for the condition of unbalance. The method of computing the best air gap as well as the mutual inductance of such transformers has been described in a previous paper.[4]

Usually 30 per cent unbalance is assumed in making computations and the formulas of the paper mentioned above are directly applicable if the direct current is assumed to flow in only one winding with a value 30 per cent as large as the actual average value in that winding. This procedure will result in the maximum possible mutual effect for the condition of unbalance stated. For the balanced condition, the mutual inductance will not be as great as could be obtained with a smaller air gap, but it will be higher than obtained at either extreme of unbalance.

Appendix I. Stability of System With Three Time Delays and Three Damping Transformers

Consider the circuit of figure 8, wherein the time delays are caused by the field circuits of the successive machines. In any one field circuit, the current and voltage are related according to the equation

$$Ri + Lpi = e \qquad (1)$$

where p is the time derivative operator. This may be written

$$i = \frac{e}{R + Lp} = \frac{e}{R} \times \frac{1}{1 + Tp} \qquad (2)$$

where $T = L/R$ the time constant of the circuit.

It is well known that for the case of a suddenly applied fixed voltage to such a circuit, the current will ultimately reach a value e/R, rising to within $1/\epsilon$ of this in time T. The quantity $(1 + Tp)$ appearing in the denominator of equation 2 may, therefore, be thought of as a time delay operator in the differential equation. This is much the same as the representation of lag or delay by $a + jb$ when this appears in a

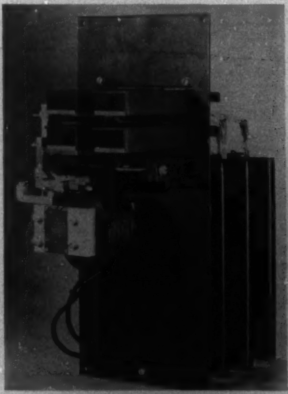


Figure 11. Silverstat relay

denominator of an expression for an a-c vector.

In the present case, it will be assumed that changes in field voltage ultimately appear as increased generated voltage in a one-to-one ratio. All currents and voltages shown will be considered as changes or deviations. During a transient, the change in generated voltage will, therefore, equal the iR drop in the field circuit. That is, for example:

$$e_3 = i_2R_2 = e_2 \times \frac{1}{1 + T_2p} \tag{3}$$

Rewriting this as

$$e_2 = e_3\,(1 + T_2p) \tag{4}$$

indicates that changes in e_2 occur ahead of changes in e_3 as represented by $(1 + T_2p)$ because the factor now appears in the numerator.

Similarly

$$\begin{aligned} e_1 &= e_2\,(1 + T_1p) \\ &= e_3\,(1 + T_2p)(1 + T_1p) \end{aligned} \tag{5}$$

and

$$\begin{aligned} e_0 &= e_1\,(1 + T_0p) \\ &= e_3\,(1 + T_2p)(1 + T_1p)(1 + T_0p) \end{aligned} \tag{6}$$

Another relation between e_0 and e_3 will now be derived by considering e_0 as the amplified input voltage which is made up of e_3 and the induced voltages in the damping transformer secondaries. In any of the transformers, the secondary voltage is related to the primary current by

$$e_s = Mpi_p \tag{7}$$

where M is the mutual inductance.

In actual designs of transformers, the primary resistance predominates over its self-inductive effect so that

$$i_p = \frac{e_p}{R_p} \text{ approximately} \tag{8}$$

Therefore

$$e_s = \frac{M}{R_p}pe_p = tpe_p \tag{9}$$

where $t = M/Rp$ represents the time constant of the damping transformers. Letting $-\alpha$* represent the voltage amplification

$$e_0 = -\alpha(e_3 + t_3pe_3 + t_2pe_2 + t_1pe_1) \tag{10}$$

Substituting for e_2 and e_1, their equivalents as given by equations 4 and 5

$$\begin{aligned} e_0 = -\alpha e_3\,[1 + t_3p + t_2p(1 + T_2p) + \\ t_1p\,(1 + T_1p)(1 + T_2p)] \end{aligned} \tag{11}$$

The complete relation from which stability and damping characteristics may be computed is obtained by equating the two values of e_0 as given by equations 6 and 11.

$$\begin{aligned} e_3(1 + T_2p)(1 + T_1p)(1 + T_0p) = \\ -\alpha e_3\,[1 + t_3p + t_2p\,(1 + T_2p) + \\ t_1p\,(1 + T_1p)(1 + T_2p)] \end{aligned} \tag{12}$$

Equation 12 may be used in computing circuits having fewer time delays or damping transformers by setting the proper T or t equal to zero. The complete relation will be used in this appendix to give a better physical understanding of the action of the transformers. If we let

$$\frac{t_3}{T_2} = \frac{t_2}{T_1} = \frac{t_1}{T_0} = 1 \tag{13}$$

that is, if the transformer time constants are each equal to the time delay which precedes them,

$$\begin{aligned} e_3(1 + T_2p)(1 + T_1p)(1 + T_0p) = \\ -\alpha e_3[1 + T_2p + T_1p\,(1 + T_2p) + \\ T_0p\,(1 + T_1p)(1 + T_2p)] = \\ -\alpha e_3\,[(1 + T_2p)(1 + T_1p)(1 + T_0p)] \end{aligned} \tag{14}$$

or

$$e_3(\alpha + 1)(1 + T_2p)(1 + T_1p)(1 + T_0p) = 0 \tag{15}$$

The solution of this differential equation for any value of amplification, no matter how large is

$$e_3 = A\epsilon^{-\frac{t}{T_0}} + B\epsilon^{-\frac{t}{T_1}} + C\epsilon^{-\frac{t}{T_2}} \tag{16}$$

which indicates very high damping of e_3 after any disturbance. It is the equating of the various transformer time constants t_1, t_2, and t_3 with the values of the preceding delays T_0, T_1, and T_2 as indicated by (13) which brought about the convenient factoring and the highly damped solution of equation 14. The transformers, therefore, may be thought of as anticipatory in their action, each taking care of one delay if made equal to that delay. If it were possible to obtain infinite amplification over an infinite range of corrective ability, the regulator would permit no departure whatever. Practically, it is possible to have very high amplification, but only for a range as limited by the size of the exciters. A suddenly changing load will, therefore, cause departure in the regulated voltage e_3, which will recover as indicated by equation 16. Within the range for which the amplification is very high, the ultimate correction will be practically perfect, however.

Appendix II. Stability of System With Three Time Delays and No Damping Transformers

Using equation 12 of appendix I, and setting $t_1 = t_2 = t_3 = 0$ as is the case in the circuit of figure 6.

$$\begin{aligned} e_3[(1 + T_2p)(1 + T_1p)(1 + \\ T_0p) + \alpha] = 0 \end{aligned} \tag{17}$$

Such a system can be stabilized if the amplification is kept below a certain value. To illustrate, let

$T_0 = 0.2$ second
$T_1 = 1$ second
$T_2 = 5$ seconds

Equation 17 becomes

$$e_3(p^3 + 6.2\,p^2 + 6.2\,p + \alpha + 1) = 0 \tag{18}$$

The requirements for stability of a system represented by a third-order linear differential equation with constant coefficients are:

1. All coefficients must be positive.
2. The product of the second and third coefficients must exceed the product of the first and fourth.

If the amplification is chosen with the correct sign, the first condition will be met. The other condition leads to

$$6.2 \times 6.2 > \alpha + 1$$

or

$$\alpha < 37.4$$

for stability.

The amplification must be considerably below this value to obtain high damping. As an example of a damping computation, let the amplification equal 13 in equation 18. Then, the roots of this equation are:

$$p = -5.53,\ -0.3325 \pm j\,1.555$$

The solution is of the form

$$\begin{aligned} e_3 = \epsilon^{-0.3325t}\,(A \cos 1.555t + \\ B \sin 1.555t) + C\epsilon^{-5.53t} \end{aligned}$$

The damped oscillatory term has a frequency

$$f = \frac{1.555}{2\pi} = 0.247 \text{ cycles per second}$$

The damping factor for one cycle is:

$$\epsilon^{-\frac{0.3325}{0.247}} = \epsilon^{-1.345} = 0.26$$

representing a decay per cycle of 74 per cent.

This method of damping a system is not satisfactory because an amplification of 13 yields only mediocre regulation. The use of damping transformers permits higher amplification, in fact, theoretically infinite amplification and is, therefore, to be preferred.

Appendix III. System With Three Time Delays and Two Damping Transformers

Appendix I dealt with an ideal system having every time delay anticipated by a feed-back rate of change effect. With very large generators, the last transformer would be of an impractical size. For this reason, it is seldom included in an actual regulator system. Figure 9 shows such a circuit. The omission of the last transformer does not cause instability or too low damping if the transformers in the other locations are properly designed. Theoretically infinite amplification is still permissible with good damping.

In equation 12, let t_3 equal zero and the amplification equal infinity. The left-hand side of the equation can then be neglected, giving:

$$\begin{aligned} e_3[1 + t_2p(1 + T_2p) + \\ t_1p(1 + T_1p)\,(1 + T_2p)] = 0 \end{aligned} \tag{19}$$

Using the same delays as in appendix II; namely,

$T_0 = 0.2 \quad T_1 = 1 \quad T_2 = 5$

---

* The negative sign is used because corrections must be opposite to deviations.

and correcting for the first two with transformers having

$t_1 = 0.2$ and $t_2 = 1$

equation 19 becomes:

$$e_1(p^3 + 6.2\,p^2 + 1.2\,p + 1) = 0$$

The roots are

$$p = -6.029,\ -0.0857 \pm j0.398$$

The solution is of the form

$$e_1 = \epsilon^{-0.0857t}(A\cos 0.398\,t + B\sin 0.398t) + C\epsilon^{-6.029t}$$

The damped oscillatory term has a frequency

$$f = \frac{0.398}{2\pi} = 0.0635 \text{ cycles per second}$$

The damping factor for one cycle is

$$\epsilon^{-\frac{0.0857}{0.0635}} = \epsilon^{-1.35} = 0.259$$

representing slightly over 74 per cent decay per cycle.

This is the same damping as obtained in appendix II without transformers, but with the amplification reduced to 13. In the present instance the amplification was assumed infinite and the regulation is, therefore, theoretically perfect.

References

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2. A GENERATOR-VOLTAGE REGULATOR WITHOUT MOVING PARTS, **C. P. West** and **I. D. Applegate.** *The Electric Journal*, April 1936, pages 181–3.

3. THE EXCITER-RHEOSTATIC REGULATOR, **A. G. Gower, Jr.** *The Electric Journal*, February 1935, page 73.

4. DESIGN OF REACTANCES AND TRANSFORMERS WHICH CARRY DIRECT CURRENT, **C. R. Hanna.** AIEE TRANSACTIONS, volume 46, February 1927, pages 155–60.

Discussion

E. E. George (Tennessee Electric Power Company, Chattanooga): This paper on generator regulators is one of the most comprehensive and interesting that has been presented to the Institute. The principle of electrical feedback is especially ingenious. The use of a feed-back transformer for stability has been tested out on a d-c telemetering receiver operating off the output of a thermocouple supplied from periodic capacitor discharge. The action of the feed-back transformer is remarkable. It is possible to damp rapid variations so that they are insignificant, although the resulting time delay in load response might be objectionable for some purposes.

The use of high gain and heavy feedback in a generator regulator at once arouses a question as to the size of equipment required. Using a large turboalternator with ordinary time constants, would not a very large main exciter be required if high-speed excitation is to be as effective as the paper would indicate? The practical application of this scheme should be followed with great interest and will do much to answer the old question as to how much real value is obtained from high-speed excitation on large alternators with a time constant of several seconds.

G. S. Lunge (General Electric Company, Schenectady, N. Y.): It is stated clearly in this paper that:

1. Direct-acting regulating devices having appropriately designed antihunting or stabilizing transformers are capable of restoring the regulated quantity to its correct value in practically aperiodic manner; that is, without subsequent oscillation.

2. The voltage introduced by such antihunting or stabilizing transformers can be of smaller magnitude and still more effective if these transformers are connected to the armature of the exciter rather than to the voltage that is being regulated.

It is interesting to note from the oscillogram in figure 5 that in the case of the particular machine tested, most of the time lag was in the exciter. It will be noted that the a-c generator field current reached its maximum value nearly as rapidly as did the exciter field current. It will also be noted that the exciter field current started to increase almost immediately that the alternating voltage dropped due to the application of load. Although this shows that the regulator response is very rapid compared with the time that it takes for the a-c machine field current to build up, this oscillogram would have been of even greater interest if it had shown just how long it took the regulator to respond, as shown, for instance, by the voltage drop across the resistance controlled by the regulator contacts. It would also have been of interest if the oscillogram had shown the complete rating, including the power factor and speed, of the a-c generator, as well as the exciter rating and nominal response.

Because the authors of this paper have used several terms interchangeably in this paper, the reader should be careful to distinguish between the two basic types of stabilizing means:

1. *Antihunting or restoring means.*

2. *Damping means*, such as provided by a dashpot or by eddy-current damping.

The first class is of preventive nature, whereas the second simply provides braking means proportional to the speed of motion of the mechanical parts, as distinct from friction braking which produces an effect practically independent of the speed of motion.

Regulators utilizing true antihunting or restoring means of proper design can eliminate, or at least mitigate, overshooting and hence removed the initial cause of temporary or sustained mechanical oscillation of the regulator, without appreciably slowing up the corrective action of the regulator. In the interest of correcting the regulated voltage promptly, a moderate amount of overshooting is desirable, hence completely aperiodic regulator action is not usually necessary in practice, although prolonged oscillations, even if damped, are objectionable.

W. K. Boice (General Electric Company, Schenectady, N. Y.): This paper recognizes the need for analytical treatment of the behavior of voltage regulating systems. It points out a means of determining characteristics of equipment for stabilizing certain idealized systems such as those shown in figures 6, 7, and 8. The actual system described in the paper and shown in figure 4 differs from these idealized regulating systems in certain fundamental respects. These include:

1. The exciter shunt field in the actual system is connected across the exciter armature and is thus affected by exciter armature voltage changes as well as impulses from the preceding step in the amplification.

2. The time delay in the regulator driving element involves an inertia effect which cannot be described by the simple first-order differential equation which expresses delays in the idealized systems.

3. The stabilizer secondary is in a current-carrying circuit, current changes in which will induce appreciable voltages in the primary.

These features are among those which were taken into consideration by a group of engineers in the General Electric Company in making a study of a practical system somewhat similar to that shown in figure 4. Results of their work have been submitted to the Institute for presentation at a future convention. ["The Direct-Acting Generator Voltage Regulator," W. K. Boice, S. B. Crary, G. Kron, and L. W. Thompson, presented at the 1939 AIEE combined summer and Pacific Coast convention, San Francisco, Calif., and scheduled for publication in the 1940 AIEE TRANSACTIONS.]

In appendix III of the paper of Messrs. Hanna, Oplinger, and Valentine, the decay of oscillations of a stabilized regulating system is shown to be 74 per cent in one cycle. It should be noted that this is one cycle at oscillation frequency, so that the decay of 74 per cent occurs in about 16 seconds which represents extremely slow decay for a practical system.

It is of interest to note that the response of the actual system is better than that indicated by the calculations in the paper.

C. R. Hanna, K. A. Oplinger, and **C. E. Valentine:** The authors wish to thank Mr. George for his generous appraisal of their paper, and agree with him that "the action of the feed-back transformer is remarkable." The regulating systems described are applicable to high-speed excitation with its attendant advantages. Large exciters will, of course, require a large damping transformer, but the size will not be excessive nor will slow regulator response be the result. For very large swings in exciter voltage, the ampere turns of the transformer are so far out of balance that the resulting saturation greatly reduces the mutual inductance. The lower feed-back effect, therefore, causes less damping for large changes in voltage than for small changes, and the recovery following the disturbance is more rapid.

Mr. Lunge states that the response of the regulator would have been indicated better if the oscillogram had included the voltage across the regulator resistance. This is true, but as he goes on to say, our oscillogram shows the exciter field current to start increasing almost immediately indicating very rapid regulator response. The authors cannot subscribe to Mr. Lunge's so-called "basic types of stabilizing means." The

Predetermination of Temperatures in Resistance Welds

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ONE of the most important variables in the resistance welding process is the temperature obtained in the region of the weld. If this temperature is too low, the parts will not unite; and if it is too high, a burned weld will result. Besides the necessity for the proper temperature at the surfaces to be joined, it is often essential to bring a considerable portion of the bodies to a plastic temperature in order that the pressure exerted by the electrodes can be transmitted to the surfaces to be joined. Furthermore, the temperature gradients and the rates of heating and cooling have an important bearing on the final quality of the weld. Consequently, it is desirable to have some method by which these quantities can be calculated.

The physical complexity of this problem has made a satisfactory mathematical solution exceedingly difficult and has limited previous theoretical analyses. A simple graphical method for solving transient heat-conduction problems has been described in the literature.[1,2,3] This analysis is here extended to apply to the present problem. The extended graphical method permits many mathematically complex conditions to be handled with ease, and routine calculations are simple enough to be performed by a draftsman. The analysis applies particularly to the resistance welding of comparatively thin sheets held between electrodes of equal contact areas, and covers a large percentage of resistance welds. It evaluates the temperatures, temperature gradients, and rates of heating and cooling of a cylindrical portion of the work enclosed between the electrodes, as functions of both time and position along the axis of this cylinder. When these quantities have been determined, a knowledge of the welding characteristics of the material will permit one to predict the quality of a weld made under given conditions, or conversely, one can predetermine important factors such as the value of current and the length of the period of current conduction which are required to produce a good weld.

The necessary knowledge of the welding characteristics of a material might be obtained by comparing the quality of welds made in this material with the calculated temperatures for those welds. Subsequent calculations would, in effect, extend the results of these few preliminary tests to apply to welds made in similar material under considerably different conditions.

The use of such analytic methods of temperature calculation should promote the more exact and rational design of welding apparatus, and should facilitate the development of new welding techniques. It should be pointed out that a calculation of temperatures does not completely solve the problem, as other variables such as pressure and surface condition of the work must be considered. However, the method presented herein permits the predetermination of the most important and most difficult to calculate of these variables.

It is therefore the purpose of this paper to present a simple and fundamental graphical method for the calculation of the temperatures obtained in comparatively thin resistance-welded material, and to compare the results of some calculations with test data.

Nature of the Problem

In spot and seam resistance-welding processes, the pieces to be welded (called the "work") are gripped between electrodes under high pressure, and an electric current is passed through the material. Heat is generated at the contacts between the two pieces of work and between the work and the electrodes, as well as in the various bodies themselves. The electrodes are made of a highly conductive material, usually a copper alloy, so that relatively little heat is generated in them. Heat is carried away from the work by the electrodes, which are usually water cooled, and is conducted laterally through the work itself. As the parts to be welded become hot and plastic, the pressure exerted by the electrodes forges the pieces together, forming a strong joint under the proper temperature and pressure conditions.

Specifically, the problem is: Given

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[1] For all numbered references, see list at end of paper.

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term "damping means" should not be restricted to dashpots or eddy-current devices which are useful in bringing to rest oscillating mechanical systems. A damped system (and Mr. Lunge himself uses the word in this sense) is one whose oscillations—electrical, mechanical, temperature, etc.—do not build up to a sustained value as in hunting, but die down to zero following a disturbance. It seems logical, therefore, to use "damping means" to connote any device which will prevent hunting of a system or cause its oscillations to decay. Contrary to Mr. Lunge's statement, there is no damping means which will not appreciably retard the corrective action of a regulator.

In order to study practical regulating systems, the authors made certain assumptions as described in the paper which greatly simplify the calculation and study of such systems. Mr. Boice has pointed this out and mentions that he and his associates are making a study of a similar system with some additional assumptions taken into consideration. This work has recently been made available in the AIEE paper referred to in his discussion and although the calculations are greatly complicated by these additional assumptions, it is gratifying to the authors to note that there is a fundamental agreement in conclusions.

With reference to Mr. Boice's comments on appendix III in which the regulator has a rapid decay per cycle, but a long period of oscillation, these calculations were made assuming infinite amplification and the omission of the last damping transformer to show that a theoretically perfect regulator with good damping is possible under such assumptions. In practice, the damping transformers will saturate for large voltage swings as described above so that the regulating system will recover much faster than indicated by the calculations. The calculations hold for small amplitudes and are of significance because they show the degree of stability for the normal rather than the exceptional condition.

The value of the stability studies reported in the paper is attested by the fact that several hundred Silverstat regulators have been placed in service and only in a few instances have even minor adjustments or changes in circuit values been necessary to give stable operation. Parallel operation of generators has been accomplished likewise with no difficulty.

the initial temperatures throughout the work and the electrodes, it is required to determine the temperature distribution at any time after the beginning of the period of current conduction.

Assumptions

In order to simplify the analysis, it has been assumed that:

1. Current flow and heat flow are essentially one-dimensional. This specifies that the current density is approximately the same throughout the portion of the work between the electrodes, and that the heat flow is mainly in a direction perpendicular to the plane of the work. This condition will be approximated where the diameter of electrode contact is somewhat greater than the thickness of the sheets to be welded, provided that the electrodes have equal contact areas. This assumption covers a large number of ordinary resistance welds.

2. The density, specific heat, and thermal conductivity of the material are independent of temperature. For the temperatures and pressures encountered in resistance welding, the densities and specific heats vary a comparatively small amount. The thermal conductivity may vary over a range of two to one, so that a mean value should be chosen. Variations in electrical conductivity, which are most important particularly in the case of ordinary steels, are taken into account.

Nature of the Analysis

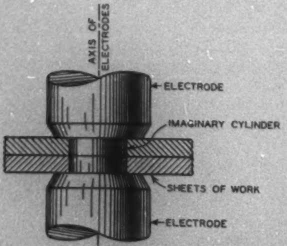

Figure 1. Cross section of weld region showing imaginary cylinder

Calculations will be made of the temperatures obtained in that part of the work compressed between the electrodes. Imagine a cylinder enclosed in this region, coaxial with the electrodes and with a radius somewhat smaller than that of the electrode contacts, as shown in figure 1. If the diameter of the electrode contacts is somewhat greater than the thickness of the sheets to be welded, both heat and current flow in the cylinder will be entirely in the direction of its axis, and any plane normal to this axis will be at a nearly uniform temperature within the cylinder. In general, the planes nearest the contact between the sheets will be at the highest temperatures, while those nearer the electrodes will be somewhat cooler because of the heat conducted away by these bodies. The material of the work surrounding the imaginary cylinder will also be cooler due to the lateral heat conduction in the sheets and because the current flow is not entirely in the direction of the axis of the cylinder in this region, but suffers "end-effects." This distribution of temperature, as shown by crystal structure, is illustrated clearly in figure 5*c*, which is a photomicrograph of the etched cross section of a weld.

The diameter of the imaginary cylinder is not a very definite quantity, but is somewhat less than the diameter of the actual weld. Photomicrographs of welds made in mild steel with conduction periods of 0.13 seconds and less, indicate that the diameter of the imaginary cylinder can be roughly approximated as $d_c = d_e - 1.5T$ where

d_c = diameter of imaginary cylinder
d_e = diameter of electrode contacts
T = total thickness of work

The above equation is purely empirical and since it is based on comparatively few experiments, it should be used only as a rough guide. As the diameter of the imaginary cylinder approaches zero, the calculated temperatures will be somewhat greater than those actually present, due to the lateral conduction of heat in the work.

In this analysis, the temperatures existing along the axis of the imaginary cylinder are plotted against distance measured along this axis, using a sequence of curves to represent successive instants of time. Each temperature distribution curve is derived from the one immediately preceding it by graphical constructions combined with simple calculations. Thus, building from known initial temperatures, one can determine the temperature distribution in the work for any later time, including both the heating and cooling periods. Temperatures, temperature gradients, and rates of heating and cooling can then be obtained from these curves.

This method of analysis is very flexible, and lends itself to a variety of assumed conditions, so long as both heat and current flow are essentially one-dimensional in that portion of the work lying near the axis of the electrodes. A convenient assumption is that the electrodes remain at a constant temperature. Since the electrodes are water-cooled in a majority of cases and are of a highly conductive material, this assumption should approximate the true condition. The thermal and electrical resistances of the several contacts should be taken into account. A method of calculating temperatures under these assumed conditions will be given first. An extension will then be described in which the heating of the electrodes is considered.

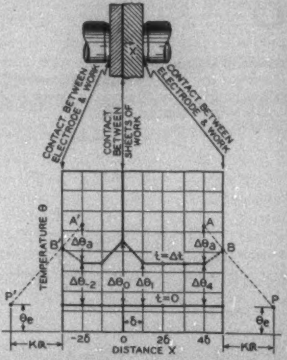
X
CONTACT BETWEEN ELECTRODE & WORK
CONTACT BETWEEN SHEETS OF WORK
CONTACT BETWEEN ELECTRODE & WORK
TEMPERATURE θ
A'
A
B'
B
Δθa
Δθa
t=Δt
Δθ-2
Δθ0
Δθ1
Δθ4
t=0
P'
P
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Figure 2a. Constructions for obtaining first two temperature-distribution curves

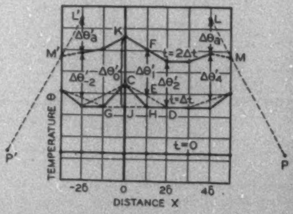

Figure 2b. Constructions for obtaining temperature-distribution curve for time t = 2Δt

Procedure in Calculating Temperatures

Simplified Method

The simplified analysis is based on the assumption that the electrodes remain at a constant temperature. Consider the electrodes and work to be sectioned through the center line of the electrodes, and the distance *x* to be measured from the plane of separation of the work out toward an electrode as shown in figure 2*a*.

The steps necessary to calculate the

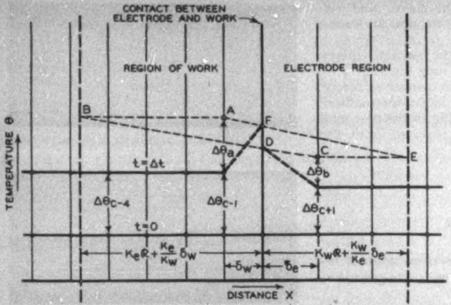

Figure 3a. Construction between work and electrode for time t = Δt; heating of electrode considered

temperature distribution curves for successive intervals of time are as follows:*

1. Select a space increment δ which will divide the thickness of the work into at least eight parts and which will permit all contacts (between sheets of work and between electrodes and work) to fall on lines of division, as in figure 2*a*. If this cannot easily be done, the position of one contact can be arbitrarily shifted a small amount so as to fall on the nearest line of division. The time interval between successive temperature distribution curves is then given by

$$\Delta t = \frac{c\rho\delta^2}{2K} \qquad (1)$$

where

Δt = increment of time
c = specific heat of the work
ρ = density of the work
δ = length of space increment
K = thermal conductivity of the work

2. Construct temperature (θ) and distance (x) co-ordinate axes, and using a suitable scale, divide the portion of the x-axis corresponding to the work into equal intervals of length δ and indicate the position of the contacts between the sheets and between the work and the electrodes, as in figure 2*a*. If the sheets are of the same thickness the contact between them will form a plane of symmetry and constructions need be made only for the material to one side of this plane.

3. As the preliminary construction for the thermal resistance between the work and the electrodes, locate the points P and P' at a distance of $K\mathcal{R}$ length units away from the electrode contacts and at an ordinate θ_e, where

$\mathcal{R}$ = thermal resistance per unit area of the electrode contact
θ_e = temperature of the electrodes

4. A horizontal line in figure 2*a* represents the uniform temperature of the work at time $t = 0$. the beginning of the period of current conduction. The temperature distribution curve for time $t = \Delta t$ is next found as in figure 2*a*. At each of the previously marked space increments within the work but not at a contact, add to the ordinate of the horizontal line an amount

$$\Delta\theta_k = \frac{m\delta^2 J^2}{2K} r_k \qquad (2)$$

where

k = an integer
$\Delta\theta_k$ = temperature increment at abscissa under consideration, $x = k\delta$
δ = length of the space increments
J = current density in the work
r_k = electrical resistivity of the material at the abscissa under consideration, $x = k\delta$
K = thermal conductivity of the work
m = a conversion factor between electrical and thermal units. If θ is in degrees Fahrenheit, J is in amperes per square inch, K is in Btu per second-inch-degree Fahrenheit, and r is in ohm-inch, then $m = 9.48 \times 10^{-4}$ Btu per watt-second

To find the temperature for time $t = \Delta t$ at the contact between the two pieces of work add to the previous temperature of the contact an amount

$$\Delta\theta_0 = \frac{m\delta^2 J^2}{2K}\left(r_0 + \frac{R_w}{\delta}\right) \qquad (3)$$

where

$\Delta\theta_0$ = temperature increment at the contact between the sheets of work
R_w = electrical resistance of the contact between the sheets of work, per unit area
r_0 = electrical resistivity of the work at the contact

To find the new temperature at the contact between the work and an electrode, first locate the point A (or A') by adding to the new temperature one interval removed from the boundary an amount

$$\Delta\theta_a = \frac{m\delta J^2}{2K} R_e \qquad (4)$$

where

R_e = electrical resistance between the electrode and the work, per unit area

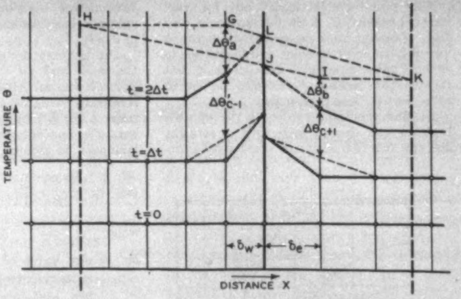

Figure 3b. Construction between work and electrode for time t = 2Δt; heating of electrode considered

Join with a straight line the points A and P (or A' and P'). The intersection B (or B') of this line with the contact indicates the new temperature at this point. Note that the point A does not indicate a temperature in the work but is only an auxiliary point used to find the contact temperature.

After the temperatures for time $t = \Delta t$ have been found for all intervals, these ordinates are joined to form a new temperature distribution curve.

The current density J may be taken to be either the instantaneous or the root-mean-square value. When the period of current passage is short, say one or two cycles in length, the alternations of the current and the resulting variations in heating may be considered. However, for longer periods it seems reasonable that the alternations should produce little effect, and the simpler procedure of using only the root-mean-square value of current could be followed.

5. The constructions for obtaining the temperatures at time $t = 2\Delta t$ are illustrated in figure 2*b*. To obtain a new temperature at an interior line of division, say at $x = k\delta$ where k is an integer, join with a straight line the two previous temperatures existing at the intervals $x = (k - 1)\delta$ and $x = (k + 1)\delta$ on opposite sides of the abscissa in question. To the ordinate of the intersection of this line with the abscissa $x = k\delta$ add the temperature increment

$$\Delta\theta_k' = \frac{m\delta^2(J')^2}{2K} r_k' \qquad (5)$$

where

$\Delta\theta_k'$ = new temperature increment at $x = k\delta$
J' = new value of current density in the work
r_k' = new value of electrical resistivity at $x = k\delta$

For example, to find the temperature for time $t = 2\Delta t$ at $x = \delta$, join points C and D (figure 2*b*) with a straight line, and to the intersection E with the line $x = \delta$, add an amount $\Delta\theta_1' = m\delta^2 (J')^2 r_1'/2K$ thus obtaining point F, which is the desired temperature.

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* For derivations of all constructions, see appendix II.

This procedure is carried out for each interval within the work but not on a contact. Observe that the resistivity r can be varied from point to point and from time to time as the temperature changes, and that the current density J can also be varied from time to time if necessary.

To find the temperature of the contact between the sheets, join with a straight line the two temperatures previously existing at the lines of division on opposite sides of that boundary (points G and H in figure 2b), and add to the intersection J of that line with the contact, the temperature

$$\Delta\theta_0' = \frac{m\delta^2(J')^2}{2K}\left(r_0' + \frac{R_w'}{\delta}\right) \tag{6}$$

where

r_0' = new value of electrical resistivity of the work at the contact
R_w' = new value of electrical contact resistance between sheets of work, per unit area

thus obtaining the new contact temperature, point K.

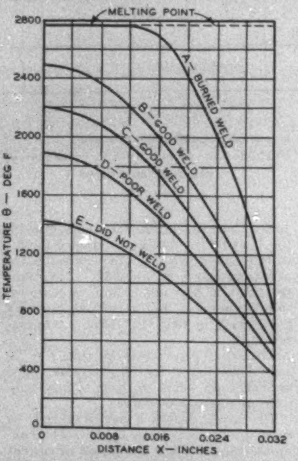


Figure 4. Calculated temperature distribution curves for ends of conduction periods; spot-welded mild-steel sheets

Curve A— $J = 4.38 \times 10^5$ amperes per square inch, two cycles

Curve B— $J = 2.42 \times 10^5$ amperes per square inch, eight cycles

Curve C— $J = 2.95 \times 10^5$ amperes per square inch, four cycles

Curve D— $J = 5.38 \times 10^5$ amperes per square inch, one cycle

Curve E— $J = 2.70 \times 10^5$ amperes per square inch four cycles

If the two sheets of work are identical, the construction line corresponding to GJH in figure 2b will be horizontal for each temperature distribution curve and calculations need be made for positive values of x only.

The temperature at the contact between the work and an electrode for time $t = 2\Delta t$ is found in the same manner as before. Referring to figure 2b, locate an auxiliary point L (or L') by adding to the new temperature one interval removed from the boundary an amount

$$\Delta\theta_a' = \frac{m\delta(J')^2}{2K} R_e' \tag{7}$$

where

R_e' = new value of electrical contact resistance between electrode and work, per unit area

Draw the straight line LP (or $L'P'$). The intersection M (or M') of this line with the contact indicates the new temperature at this point.

It will be seen that the constructions given under (4) are special cases of the later constructions and differ from them only because the initial temperature distribution was a horizontal line.

When the temperatures for time $t = 2\Delta t$ have been found for all points these ordinates are joined to form the temperature distribution curve for this time.

6. This process is continued building curve upon curve for successive intervals of time, changing the current density and resistivity as necessary. When the end of the period of current conduction is reached the current density J is set equal to zero and the temperature curves are derived only by the graphical constructions. In this way the temperatures during the cooling of the work can be calculated.

The temperature distribution curve for any given time indicates the temperatures and temperature gradients in the material, and the rates of heating and cooling for any point can be derived from successive curves.

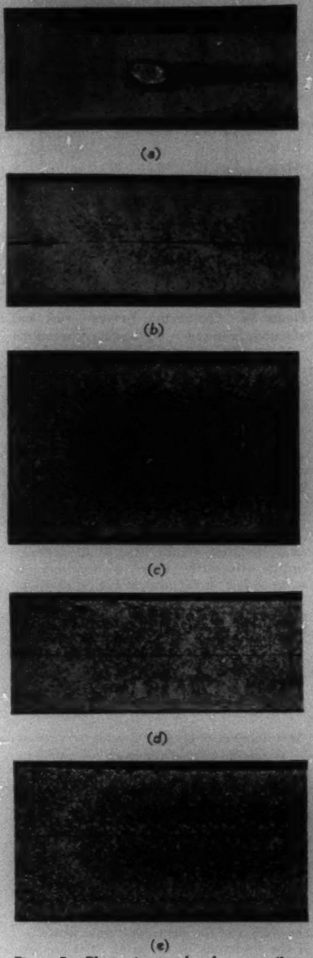
EXTENSION OF METHOD: HEATING OF ELECTRODES

A method for taking into consideration the heating of the electrodes will now be described. The extended method differs from that previously described mainly in that the portions of the x axis corresponding to the electrodes are now also divided into increments of equal length, and calculations are continued into the electrode regions.

The length of the intervals in the electrode regions must differ from the length of the increments in the work. Letting the subscript e refer to the electrode and the subscript w refer to the work, the relation between the increments in the two regions is given by

$$\delta_e = \delta_w \sqrt{\frac{C_w\rho_w K_e}{C_e\rho_e K_w}} \tag{8}$$

Temperature (θ) and distance (x) co-ordinate axes are first constructed, and the space increments for the work and the electrodes are drawn, taking care to make the lengths of the increments in the two regions satisfy equation 8.


(a)

(b)

(c)

(d)

(e)

Figure 5. Photomicrographs of cross sections of welds. Center lines of welds at right of pictures

As a preliminary construction for the thermal resistance at the contact between the work and each electrode, draw a vertical line in the region of the work at a distance $K_e\mathfrak{R} + \delta_w K_e/K_w$ from the contact line, as shown in figure 3a, and another vertical line in the region of the electrode at a distance $K_w\mathfrak{R} + \delta_e K_w/K_e$ from the contact.

Starting with an initial uniform temperature distribution for time $t = 0$, the temperatures in the interior of the work and the electrodes are found for time $t = \Delta t$ by the method first described for interior points, and the construction for the contact between the sheets of work remains the same as before. At the contact between an electrode and the work the construction shown in figure 3*a* is necessary. To the new temperature one interval removed from the electrode contact and in the region of the work, add an amount

$$\Delta\theta_a = \frac{m\delta_w J^2}{2K_w} R_e \qquad (9)$$

thus obtaining the new ordinate A in figure 3*a*. To the temperature in the electrode region one interval removed from the contact, add the temperature

$$\Delta\theta_b = \frac{m\delta_e J^2}{2K_e} R_e \qquad (10)$$

obtaining a new ordinate C in figure 3*a*. Draw the horizontal lines AB and CE, and from the intersections of these lines with the vertical construction lines, draw the straight lines AE and BC. The intersection F of the line AE with the contact indicates the new temperature on the work side of the contact, and the intersection D of the line BC with the contact indicates the new temperature on the electrode side of the contact. The temperature distribution curve is then completed as shown by the heavy dotted lines.

The temperature distribution curve for time $t = \Delta t$ is then used to construct the temperature curve for time $t = 2\Delta t$, as shown in figure 3*b*. Interior temperatures are found by the method described in a previous section. To obtain the electrode contact temperature, locate point G by adding to the temperature at that abscissa the amount

$$\Delta\theta_a' = \frac{m\delta_w (J')^2}{2K_w} R_e' \qquad (11)$$

where

J' = new value of current density
R_e' = new value of electrical resistance between the electrode and the work, per unit area

Locate point I by adding to the ordinate at that abscissa the temperature

$$\Delta\theta_b' = \frac{m\delta_e (J')^2}{2K_e} R_e' \qquad (12)$$

Draw the horizontal lines GH and IK, and the straight lines GK and HI. The intersection L of GK with the contact indicates the temperature on the work side of the contact, and the intersection J of HI with the contact indicates the temperature on the electrode side of the contact. The temperature curve is completed as shown by the heavy dotted lines.

By building each temperature distribution curve upon the one preceding it, the process can be continued until the desired period of time has been covered.

Comparison With Test Results

In order to test the method of analysis and to check the assumptions, calculations were made for the spot welding of low-carbon-steel sheets for various values of current density and for different lengths of current passage, and test welds were made under these conditions. Low carbon steel was chosen for these welds because its properties were quite well known and because its steeply rising electrical resistivity versus temperature characteristic would impose a severe test on the analysis. Since the direct measurement of temperatures in the welds would be quite difficult, and since the temperatures evidently bear a close relation to weld quality, the calculated maximum temperatures in the region of the weld were compared directly with the quality of the test welds. Photomicrographs were made of the cross sections of the various welds, and the structures which these revealed were also compared with the calculated temperatures.

Each test weld was made between two sheets of 0.032-inch low carbon steel, using electrodes with a contact diameter of about 0.25 inches. The electrode pressure in each case was approximately 700 pounds. Calculations of current density were based on the carefully measured actual area of contact between the electrodes and the sheets. A lack of data on the thermal resistance of contacts under high pressures made necessary the assumption that the electrical and thermal resistances of a contact bear the same approximate relation as do the electrical resistivity and the thermal resistivity (reciprocal of thermal conductivity) of the work. To simplify the calculations, the electrode temperatures were assumed to remain constant.

The temperatures calculated for the end of the period of current conduction for several cases are shown in figure 4, and photomicrographs of the cross sections of these welds are shown in figure 5. The interior temperatures necessary to produce a good weld check quite well for widely varying conditions of current and time, as do the temperatures calculated for the dark regions of carbide precipitation shown in the photomicrographs of figure 5. It appears that a maximum temperature of over 2,000 degrees Fahrenheit is necessary to produce a good weld in this material. It is interesting to observe that curve A of figure 4 indicates that a considerable portion of the work had reached melting temperature, and that the corresponding photomicrograph (figure 5*a*) shows a proportional reduction in the thickness of the work at the weld. Curve B of figure 4 indicates that the proper welding temperatures have been obtained, and this weld was indeed quite strong, although the photomicrograph (figure 5*b*) does not show the grain structure ordinarily considered typical of a good weld. Higher magnification showed that the dark line of apparent separation was really composed of fine interlaced grains, forming a strong weld. Curves C, D, and E of figure 4 illustrate strikingly the differences between the calculated temperatures in good and poor welds, and the corresponding photomicrographs (figure 5*c*, *d*, *e*) show the expected differences in structure.

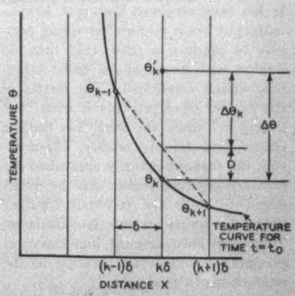


Figure 6. Graphical construction for obtaining temperature increment during time Δt

The maximum temperatures calculated for the interior of these welds are seen to compare quite well with the quality of the welds. Furthermore, the calculated temperatures are reasonable in value and agree with the observations of other investigators. Larsen[4] states that recrystallization across the plane of contact is the fundamental phenomenon of resistance welding. Recrystallization is favored by a state of strain and occurs in steel at temperatures somewhat below the melting point of approximately 2,800 degrees Fahrenheit. Larsen mentions welding temperatures of from 1,750 degrees Fahrenheit to 2,400 degrees Fahrenheit for mild steel, and Spraragen and Claussen[6] give data deduced from microstructural observation which indicate maximum temperatures of about 2,300 degrees Fahrenheit, which check quite well with the present results.

Effect of Pressure and Contact Area

The exact nature of a resistance weld in ferrous materials is difficult to determine, since the physical metallurgy of metals under high pressures has been investigated but little, and any discussion of this subject must therefore be somewhat speculative. It is reasonable to believe, however, that the welding operation in ferrous materials is a forging process, in which the adjacent portions of the bodies are brought to a sufficiently plastic state while under pressure, thus causing the metals to unite.

It should be pointed out that both pressure and temperature are requisite to the production of a good weld. It is well known that a weld in heavy materials requires comparatively low currents and long times of application, so that the metal will be heated throughout its thickness. Apparently this is necessary in order to render the material so plastic that sufficient pressure will be transmitted to the surface between the bodies to cause the forging action to take place. It has been observed that spot welders with light heads require less spring pressure to produce a good weld than do welders with heavy heads, under otherwise similar conditions. The inertia of the heavier head prevents it from "following in" when the work has become plastic, and deforms readily. As a result, the pressure actually applied to the high temperature region may be insufficient to forge the materials together unless the spring pressure is quite large. This again illustrates the importance of pressure as well as temperature in the production of a good weld.

Because the heat generated per unit volume of the work varies as the square of the current density, it is necessary to know the electrode contact area, as well as the total current, quite accurately, in order to make satisfactory calculations. This is shown by curves *C* and *E* of figure 4, between which the current density varied less than ten per cent. The effect is here accentuated, of course, by the sharply rising electrical resistivity versus temperature characteristic of the low carbon steel. These curves illustrate the fact that accurate control of electrode contact area is necessary in order to secure consistently good welds with a given transformer tap and conduction period. This necessity has already been emphasized by welding engineers.

In the case of electrodes of small contact area and with work of considerable thickness, the assumptions used in this analysis will not be valid, since current density will not be uniform and heat flow in the plane of the work may be considerable. To cover these cases, some sort of three-dimensional treatment may be necessary.

Conclusions

The method of analysis described herein is believed to be based upon fundamentally correct principles, and has been shown by comparison with test results to permit a prediction of the temperatures which will be obtained in comparatively thin resistance-welded material. The relation between temperature and weld quality for a given material can be established by comparing preliminary calculations with the results of comparatively few tests. Predictions of weld quality can then be extended to other thicknesses of this material and to various currents and periods of current conduction without further tests.

The constructions are simple, and routine calculations can be made by a draftsman. If desired, the computations can be carried out numerically in tabular form, instead of using the graphical constructions described in this analysis.

Although this method of analysis has been used only in spot-welding calculations, it should apply also to seam welding, and, under some conditions, to butt welding. The use of such methods of analysis should facilitate the development of welding processes, and should be an aid in the design of new welding apparatus.

Appendix I. Nomenclature

C = specific heat
C_e = specific heat of the electrode
C_w = specific heat of the work
D = temperature increment obtained by graphical construction
J = current density
K = thermal conductivity
K_e = thermal conductivity of the electrode
K_w = thermal conductivity of the work
k = an integer
m = conversion factor between electrical and thermal units
Q = rate of heat conduction across a plane, per unit area
q = rate of heat generation, per unit volume
R_e = electrical resistance per unit area of the electrode contact
R_w = electrical resistance per unit area of the contact between sheets of work
$\mathcal{R}$ = thermal resistance per unit area of the electrode contact
r_k = electrical resistivity of the material at the abscissa $x = k\delta$
r_0 = electrical resistivity of the work at the contact between sheets
t = time measured from the beginning of current conduction
Δt = time increment between successive temperature distribution curves
x = distance measured from the contact between sheets of work, parallel to heat flow
δ = length of space increment
δ_e = length of space increment in the electrode region
δ_w = length of space increment in the region of the work
θ = temperature
θ_{ce} = temperature of the electrode at the plane of contact
θ_{cw} = temperature of the work at the electrode contact
θ_e = electrode temperature
θ_{e+1} = electrode temperature one interval removed from the plane of the contact
θ_{c-1} = temperature of the work one interval removed from the electrode contact
θ_k = temperature existing at the abscissa $x = k\delta$
$\Delta\theta$ = total temperature increment during time Δt
$\Delta\theta_a$, $\Delta\theta_b$ = temperature increments to obtain construction points
$\Delta\theta_k$ = temperature increment at abscissa $x = k\delta$ due to generation of heat
$\Delta\theta_0$ = temperature increment at contact between sheets due to generation of heat
ρ = density of the material
ρ_e = density of the electrode
ρ_w = density of the work

Primed quantities refer to the values of increments and parameters occurring at a later time than the unprimed quantities.

Appendix II. Derivations

Constructions for Interior of Body

This analysis depends upon the replacement of first and second derivatives in the heat-flow equations with quotients of finite differences. By this replacement a step-by-step approximate solution may be obtained.

The partial differential equation of heat flow for the case of constant thermal conductivity can be shown to be

$$C\rho \frac{\partial\theta}{\partial t} = K\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + q \qquad (13)$$

where

C = specific heat
ρ = density
K = thermal conductivity
θ = temperature
t = time
q = rate of heat generation per unit volume

Where the heat flow is unidimensional equation 13 reduces to

$$C\rho \frac{\partial\theta}{\partial t} = K \frac{\partial^2\theta}{\partial x^2} + q \qquad (14)$$

By definition of a derivative

$$\frac{\partial\theta}{\partial t} = \lim_{\Delta t \to 0} \frac{\Delta\theta}{\Delta t} \qquad (15)$$

where

$\Delta\theta$ = finite increment of temperature
Δt = finite interval of time

or approximately

$$\frac{\partial\theta}{\partial t} = \frac{\Delta\theta}{\Delta t} \qquad (16)$$

provided that the time increment Δt is taken to be reasonably small. If we now divide the desired span of x into equal small intervals of width δ we can approximate the temperature gradients at points $x = k\delta$ and $x = (k+1)\delta$ in figure 6 by

$$\left.\frac{\partial\theta}{\partial x}\right|_{k+1} = \frac{\theta_{k+1} - \theta_k}{\delta}$$

and

$$\left.\frac{\partial\theta}{\partial x}\right|_{k} = \frac{\theta_k - \theta_{k-1}}{\delta} \qquad (17)$$

where θ_{k+1} θ_k and θ_{k-1} are the temperatures existing at time $t = t_0$ at the abscissas $(k+1)\,\delta$, $k\delta$, and $(k-1)\delta$, respectively.

By definition,

$$\left.\frac{\partial^2\theta}{\partial x^2}\right|_k = \lim_{\delta \to 0}\left(\frac{\left.\frac{\partial\theta}{\partial x}\right|_{k+1} - \left.\frac{\partial\theta}{\partial x}\right|_k}{\delta}\right)$$

or approximately, provided that δ is quite small, we obtain by substituting equations 17,

$$\left.\frac{\partial^2\theta}{\partial x^2}\right|_k = \frac{\theta_{k+1} + \theta_{k-1} - 2\theta_k}{\delta^2} \qquad (18)$$

Substituting the approximations expressed by equations 16 and 18 into the differential equation 14, we obtain for the increase in temperature at $x = k\delta$ during time Δt,

$$\Delta\theta = \frac{K\,\Delta t}{C\rho\delta^2}(\theta_{k+1} + \theta_{k-1} - 2\theta_k) + \frac{q\,\Delta t}{C\rho} \qquad (19)$$

For convenience of graphical construction, we shall let

$$\frac{K\,\Delta t}{C\rho\delta^2} = \frac{1}{2} \qquad (20)$$

For any given material, this will fix the time increment once the space increment δ is chosen. Substituting condition 20 into equation 19, there is

$$\Delta\theta = \frac{1}{2}(\theta_{k+1} + \theta_{k-1} - 2\theta_k) + \frac{\delta^2 q}{2K} \qquad (21)$$

The rate of heat generation is

$$q = mJ^2 r_k \qquad (22)$$

where

J = current density
r_k = resistivity of the material at $x = k$
m = conversion factor between electrical and thermal units

If q is in Btu per second-inch³, J is in amperes per inch², and r_k is in ohm-inch, then $m = 9.48 \times 10^{-4}$ Btu per watt-second.

Substituting equation 22 into equation 21, we obtain for the total temperature increase at $x = k\delta$ during the time Δt,

$$\Delta\theta = \frac{1}{2}(\theta_{k+1} + \theta_{k-1} - 2\theta_k) + \frac{m\delta^2 J^2 r_k}{2K} \qquad (23)$$

Consideration of figure 6 will show that the quantity

$$\frac{1}{2}(\theta_{k+1} + \theta_{k-1} - 2\theta_k)$$

is the difference between the ordinate θ_k at x_0 and the chord joining θ_{k-1} and θ_{k+1}, and may be obtained graphically.

Equation 23 can be rewritten as

$$\Delta\theta = D + \Delta\theta_k$$

where

$$D = \frac{1}{2}(\theta_{k+1} + \theta_{k-1} - 2\theta_k) \qquad (24)$$

$$\Delta\theta_k = \frac{m\delta^2 J^2}{2K} r_k$$

This affords a convenient graphical construction. Given the temperature distribution at time t_0, the temperature of a plane, say at $x = k\delta$, for time $t_0 + \Delta t$, can be found by first joining the ordinates θ_{k-1} and θ_{k+1} with a straight line (figure 6). The intersection of this line with the trace $x = k\delta$ indicates the temperature which this point would have attained at time $t_0 + \Delta t$ if no heat were generated in the element, and represents the increment D. If to this ordinate is added the quantity $m\delta^2 J^2 r_k/2K$ as indicated by equation 24, the result will be the temperature θ_k' at time $t_0 + \Delta t$. In this way a new temperature distribution for the time $t_0 + \Delta t$ can be constructed from the temperature curve for time t_0.

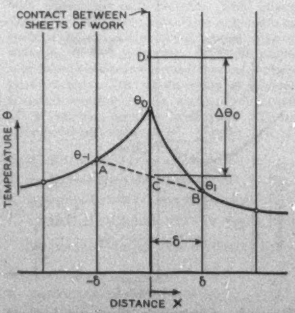


Figure 7. Construction at contact between sheets of work

It will be observed that the resistivity r_k can be regarded as varying from increment to increment and from time to time. This variation can be determined most conveniently from a resistivity versus temperature curve.

Boundary Conditions

The above-described conditions will suffice for the interior of a body, but further considerations are necessary for the boundaries.

CONTACT BETWEEN SHEETS OF WORK

The construction at the contact between sheets of work is similar to that used for the interior of the sheets, except that the heat generated by the electrical resistance of the contact must be added to that generated in this increment by the electrical resistivity of the work. Since the constructions are based on the space increment as a unit, the electrical contact resistance may be reduced to an equivalent electrical resistivity distributed throughout the space increment at the contact. The rate of heat generation per unit volume of the work in this increment is given by the expression

$$q = mJ^2\left(r_0 + \frac{R_w}{\delta}\right) \qquad (25)$$

where

R_w = electrical resistance of the contact between the sheets of work, per unit area

Substituting equation 25 into 21, the equation which applies to the temperature increment at the contact is found to be

$$\Delta\theta = D + \Delta\theta_0 \qquad (26)$$

where

$$D = \frac{1}{2}(\theta_1 + \theta_{-1} - 2\theta_0)$$

$$\Delta\theta_0 = \frac{m\delta^2 J^2}{2K}\left(r_0 + \frac{R_w}{\delta}\right)$$

This indicates that to obtain the new temperature at the contact between the sheets of work, connect with a straight line the previous temperatures existing on opposite sides of the junction (points A and B in figure 7), and to the ordinate (C) of the intersection with the contact, add the temperature increment $\Delta\theta_0$ as given by equation 26. The resulting ordinate (D) will indicate the new temperature at the contact. Observe that if the construction is symmetrical about the contact, as would be the case with two identical sheets of work, points A and B will be at the same ordinate. It is then necessary to make calculations for the material to one side of the junction only, and since the line BC is then horizontal, the temperature increment at the contact is measured above this ordinate.

CONTACT BETWEEN WORK AND ELECTRODE: ELECTRODE AT CONSTANT TEMPERATURE

The contact between the electrode and the work is considered to offer a resistance to the flow of both heat and current, and the temperature of the electrode is here assumed to be constant. The thermal resistance of the contact is defined by the equation

$$\mathcal{R} = \frac{\theta_{cw} - \theta_e}{Q} \tag{27}$$

where

$\mathcal{R}$ = thermal resistance of the contact, per unit area
Q = rate of heat conduction across the contact, per unit area
θ_{cw} = temperature of the work at the contact
θ_e = temperature of the electrode

The heat passing across the thermal resistance of the contact is taken to be equal to the heat conducted to the contact from the work plus one-half of the total heat generated at the contact. This is equivalent to assuming that heat is generated uniformly throughout the thickness of the contact resistance. The rate of heat conduction is, from elementary theory, equal to $-K\partial\theta/\partial x$, so the heat crossing the contact is given by the expression

$$Q = \frac{K(\theta_{c-1} - \theta_{cw})}{\delta} + \frac{mJ^2R_e}{2} \tag{28}$$

where

R_e = electrical resistance of the contact between the electrode and work, per unit area
θ_{c-1} = temperature of the work one interval removed from the contact

Eliminating Q between (27) and (28), we obtain the expression

$$\frac{\theta_{cw} - \theta_e}{K\mathcal{R}} = \frac{\theta_{c-1} - \theta_{cw} + \Delta\theta_a}{\delta} \tag{29}$$

where

$$\Delta\theta_a = \frac{m\delta J^2R_e}{2K} \tag{30}$$

Equation 29 suggests the similar triangle construction shown in figure 8. Here we see that

$$\frac{BD}{DP} = \frac{AC}{CB}$$

which implies the relation expressed by equation 29. In this construction the point P is located at a distance $K\mathcal{R}$ length units away from the contact and at a temperature θ_e. Given the temperatures θ_{c-1} and θ_e at time t, the temperature at the junction, θ_{cw}, is determined by adding to the ordinate θ_{c-1} an amount $\Delta\theta_a$, thus obtaining the point A, and drawing the straight line AP. The intersection B of the straight line with the contact indicates the temperature of the junction, θ_{cw}.

CONTACT BETWEEN WORK AND ELECTRODE: HEATING OF ELECTRODE CONSIDERED

In this construction, both the electrodes and the work are divided into increments, and calculations are carried into the electrode regions.

The time interval, Δt, between successive temperature curves, must be the same for both electrode and work regions. Letting the subscripts e and w refer to the electrode and work respectively, we obtain from equation 20 the relation

$$\Delta t = \frac{C_e\rho_e\delta_e^2}{2K_e} = \frac{C_w\rho_w\delta_w^2}{2K_w} \tag{31}$$

To satisfy equation 31, the space increments in the two regions must be in the ratio

$$\frac{\delta_e}{\delta_w} = \sqrt{\frac{C_w\rho_wK_e}{C_e\rho_eK_w}} \tag{32}$$

The heat carried across the contact between the work and an electrode is taken, as before, to be equal to the heat conducted to the contact from the work plus one-half of the heat generated in the electrical resistance of the contact. Thus,

$$Q = \frac{K_w}{\delta_w}(\theta_{c-1} - \theta_{cw}) + \frac{mJ^2R_e}{2} \tag{33}$$

where

Q = rate of heat conduction across the contact
Q_{cw} = temperature of the work at the contact
θ_{c-1} = temperature of the work one interval removed from the contact
K_w = thermal conductivity of the work
R_e = electrical resistance of the contact between the work and the electrode, per unit area

The heat conducted from the contact into the electrode is equal to that passing through the contact plus the remainder of the heat generated at the contact, and may be expressed as

$$Q + \frac{mJ^2R_e'}{2} = \frac{K_e}{\delta_e}(\theta_{ce} - \theta_{e+1}) \tag{34}$$

where

K_e = thermal conductivity of the work
θ_{ce} = temperature of the electrode at the contact
θ_{e+1} = temperature of the electrode one interval removed from the contact

The heat passing through the thermal resistance of the contact causes a temperature difference between the work and electrode sides of the contact, or

$$Q = \frac{\theta_{cw} - \theta_{ce}}{\mathcal{R}} \tag{35}$$

where

$\mathcal{R}$ = thermal resistance of the contact, per unit area

Equate (33) and (35) and obtain

$$(\theta_{cw} - \theta_{ce})\delta_w = K_w\mathcal{R}\left(\theta_{c-1} - \theta_{cw} + \frac{m\delta_wJ^2R_e}{2K_w}\right) \tag{36}$$

Eliminating Q between equations 33 and 34 and solving for θ_{ce}, there is

$$\theta_{ce} = \theta_{c+1} + \frac{\delta_eK_w}{\delta_wK_e} \times \left(\theta_{c-1} - \theta_{cw} + \frac{m\delta_wJ^2R_e}{2K_w}\right) \tag{37}$$

Substituting equation 37 into equation 36 to eliminate θ_{ce} and simplifying, we obtain the relation

$$\frac{\theta_{cw} - \theta_{c+1} - \Delta\theta_b}{K_w\mathcal{R} + \frac{K_w}{K_e}\delta_e} = \frac{\theta_{c-1} - \theta_{cw} + \Delta\theta_a}{\delta_w} \tag{38}$$

where

$$\Delta\theta_a = \frac{m\delta_wJ^2}{2K_w}R_e$$
$$\Delta\theta_b = \frac{m\delta_eJ^2}{2K_e}R_e \tag{39}$$

which will be used in the construction to obtain θ_{cw}.

Now eliminate Q between equations 34 and 35 and between equations 33 and 34, and from the resulting two equations eliminate θ_{cw}. The result can be expressed as

$$\frac{\theta_{c-1} - \theta_{ce} + \Delta\theta_a}{K_e\mathcal{R} + \frac{K_e}{K_w}\delta_w} = \frac{\theta_{ce} - \theta_{c+1} - \Delta\theta_b}{\delta_e} \tag{40}$$

which is the relation which will be used in the construction to obtain θ_{ce}.

Figure 9 illustrates the procedure for this case. A construction line is first drawn in the region of the work, parallel to the temperature axis, at a distance $K_e\mathcal{R} + \delta_wK_e/K_w$ from the contact, and a similar line is drawn in the region of the electrode at a distance $K_w\mathcal{R} + \delta_eK_w/K_e$ from the contact.

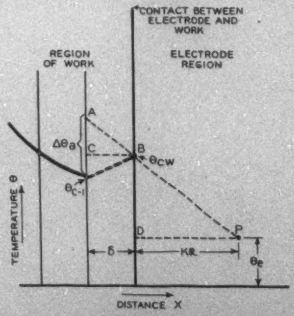


Figure 8. Construction at contact between work and electrode; electrode at constant temperature

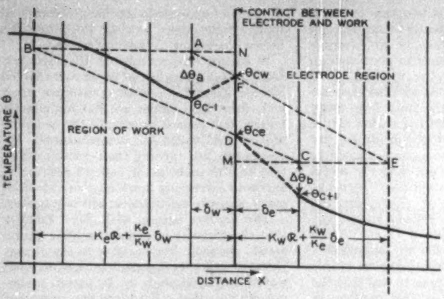


Figure 9. Construction at contact between work and electrode; heating of electrode considered

Given the temperatures θ_{c-1} and θ_{c+1} at the intervals on opposite sides of the contact, add to the ordinate θ_{c-1} an amount $\Delta\theta_a$ and add to θ_{c+1} an amount $\Delta\theta_b$, thus obtaining the new ordinates A and C.

Draw the horizontal line CE, and connect E and A with a straight line. The intersection F of this line with the contact indicates the temperature of the work at the contact, θ_{cw}. Inspection of figure 9 will show that, by similar triangles, $FM/ME = FN/NA$, which is the relation expressed by equation 38.

Draw the horizontal line AB and connect B with C. The intersection D of BC with the contact indicates the electrode temperature at the contact, θ_{ce}. In this construction, $DN/NB = DM/MC$, which is the relation given by equation 40.

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Discussion

R. H. Harrington (nonmember; General Electric Company, Schenectady, N. Y.): Mr. Johnson presents in this paper some very fine work concerning a difficult problem. The fundamental-research committee of the American Welding Society is extremely interested in this specific problem and the writer commends this fine paper to their detailed attention.

One of the fundamental problems still beset by disagreement among resistance-welding engineers is just this: "Is the best resistance weld achieved by actual melting at the interface of the work or by grain growth across this junction while the steel is in a plastic condition?"

From the metallurgical viewpoint the writer fully agrees with Mr. Johnson that the best welds should result from grain growth across the junction of the work while the steel is under pressure in the plastic range. Some applications, it is true, will require actual melting at the interface because of inherent conditions but these applications must then be satisfied with properties inferior to those of welds produced in the solid state. Of course, these statements apply only to steels.

Until quite recently we have all of us largely neglected the effect of strain (internal tension and pressure) on reactions in the solid state in metals and alloys. It is good to have Mr. Johnson call attention to this fact. The rates of grain growth, diffusion, and phase reactions are bound to be affected in some degree when the system is kept under a continuously applied strain. The tendency has been, in application of the phase rule to alloy systems, to assume that the pressure in the system is atmospheric when this is rarely true, and, in the case of resistance welding, far from true.

R. J. Bondley (nonmember; General Electric Company, Schenectady, N. Y.): The paper "Prediction of Temperatures in Resistance Welds" is an excellent bit of mathematical analysis. The author has verified by calculation the facts that have been found by experiment. The paper should be of interest to welding engineers or students doing advanced work on resistance welding. I feel, however, that the paper is of more academic interest than of a practical nature. The whole analysis is constructed around certain assumptions, such as a known contact resistance. These resistances will vary with:

1. Kind of material being welded.
2. Surface condition of the metals.
3. Nature of surface and size of electrodes.
4. Pressure of electrodes, especially during weld

The pressure during weld is affected by:

1. Inertia of the moving parts.
2. Bearing friction of moving parts.
3. Inductive reaction of the welding arms.

When one considers that a ten per cent change in current may mean the difference between a good and a poor weld, it is clear that the assumptions may be well over ten per cent off.

As for the predetermination of welding capacity as claimed by the author, capacity of welders for any application is well known to persons acquainted with the resistance welding art.

Likewise as to quality of welds, I believe that with modern welding equipment, the results can be obtained much quicker and with greater accuracy by experiment than by calculation.

L. G. Levoy (General Electric Company, Schenectady, N. Y.): Mr. Johnson is to be congratulated for applying a method of analysis to this difficult problem, and seeing it through in spite of the difficulties presented by unknown relations, including variations in parameters which are beyond the scope of the analysis.

The value of such calculations lies in their ability to show what effect variation in time, current density, and other variables considered, have upon the work. Prior to now most ideas concerning these factors were more or less empirical and based mainly upon experimental work. Application of this analysis, though not precise, will give a better understanding of what goes on in making welds. This will lead to more valuable experimentation and to the production of better welds and better welding conditions.

Resistance-welding engineers and metallurgists will welcome this study, as it provides them with an analytical approach to the internal conditions existing during the welding process.

H. D. Snively (General Electric Company, Schenectady, N. Y.): Mr. Johnson is to be congratulated for his courage in attacking such a problem as this one and for his persistence in obtaining a solution in spite of the large number of variables which have frightened away many other investigators. We are glad to see that he was able to apply the graphical method of analysis to the problem, and we welcome the opportunity to make some general remarks concerning the method. Over a period of several years we have had considerable experience with the method and have developed it for use on various special problems; and we hope to be able to publish some notes in the near future describing more completely this type of analysis and some of its applications to problems of a more difficult nature than those of one-dimensional heat flow.

We agree with the author's conclusion that the graphical method can very readily be taught to some previously uninitiated person so that he can carry out the routine graphical constructions necessary to solve any particular problem. In fact, we have had some experience in teaching the method and have found that a half hour's description of the process will usually serve completely to acquaint the person with the method so that he can carry out the solution for any particular problem although he might not be able to formulate the routine by himself.

The advanced course in engineering of the General Electric Company has on various occasions during the last several years solved complex heat conduction problems by the use of an extended form of the analysis used by Mr. Johnson, and we have noted that in most cases, after the routine procedure of solution was once launched upon, the time required to carry the solution through to a finish was a matter of three or four hours. For more simple problems the time is considerably less. The method could therefore be described as being monotonous but not excessively time-consuming.

To check the accuracy of the method of analysis we have solved problems by the graphical method which could also be solved analytically, such as the problem of transient heating of a long circular cylinder suddenly subjected to a uniform temperature all over the cylindrical surface. In this particular problem we found that when the space region (here the radius of the cylinder) was divided into ten equal segments, ten increments of time in the process of solution would bring the graphical solution to within ten per cent of the accuracy of the exact analytical solution. Twenty-five steps in time would bring the accuracy to within five per cent and 50 steps would make the graphical solution almost coincide with the exact solution. Other problems that we have dealt with indicate the same degree of accuracy. Of course an increase in the number of space increments would improve the accuracy but it also would decrease the size of the time increment so that more steps would have to be taken to cover a given period of time. In general some compromise between accuracy and time available for solution will have to be made. The conclusion is, therefore, that within the accuracy of the assumptions on any particular problem the graphical method can give very accurate results indeed.

The method could have been adapted to take into account such things as the variation of thermal conductivity which as the author has pointed out has a range of about two to one in his problem. However, the amount of work required to obtain the solution would have been greatly increased, and probably his assumption of an average thermal conductivity leads to good enough results. Furthermore, the method could have been modified so as to take into account approximately the heat flow away from the assumed cylindrical region of the weld. That is, instead of considering the heat to flow linearly from one electrode to another, the heat flow out into the metal adjacent to the weld could have been approximately taken care of. Here, too, the probable effect of this refinement on the result would be negligible.

Again we take occasion to congratulate our former colleague, Mr. Johnson, on his excellent paper, and we hope to find that the graphical method will be applied by others in solving still other types of problems.

Walter C. Johnson: The author appreciates very much the discussions of his paper, some of which require no further comment. He is pleased to find that Mr. Snively agrees with him concerning the accuracy and simplicity of the graphical method of analysis. The method undoubtedly looks more complicated on paper than it really is. A complete understanding of the analysis requires some knowledge of mathematics, but the operations themselves are relatively simple and can be readily learned without such knowledge. Mr. Snively's account of his checks on the accuracy of the graphical method are also enlightening.

As Mr. Snively points out, the assumptions of a constant thermal conductivity and of an essentially one-directional heat flow in a central region are not essential to the graphical analysis, but can be eliminated, at the expense, of course, of a more complicated and laborious solution. These refinements will probably be desirable in some types of problems, for example, when the work is of considerable thickness. The author has thought it desirable to gain additional experience in the application of the simpler analysis to specific problems and to determine more exactly its limitations before proceeding to these refinements.

It should be remembered that the test calculations given in the paper are affected by the values of contact resistance used, and since these values are but imperfectly known, one cannot be sure of the accuracy of the final calculated temperatures. Investigators are turning their serious attention to the problem of contact resistance, and with increasing knowledge in this field, more accurate calculations will be possible.

The author agrees with Mr. Bondley that the capacity of present welding equipment is well known from experience. However, the development of new methods would be facilitated by a better understanding of what takes place in a resistance weld, and by a better knowledge of the relative effect of the various important factors. A case in point is the problem for which this analysis was originally developed, in which the root-mean-square current fluctuated widely during the welding period, so that the requirements were considerably different than for an ordinary weld. This analysis was developed to permit the design of the necessary apparatus without resorting to expensive cut-and-try procedure. As for the difficulties engendered by the variation in parameters: since these factors can be controlled well enough to make consistently good welds possible, their values can probably be determined with enough certainty for successful calculation. Furthermore, the effect of a variation in parameters could probably be determined more conveniently by analytical methods than by experiment alone, since the factors could be varied at will in calculations.

The practical significance of a method of calculating temperatures would seem to lie not so much in the calculation of each set of welds in a production line as in the possibility of a better understanding of fundamental resistance-welding problems, and in the provision of a helpful tool for their solution.

Electrical Equipment Used in Reflection-Seismograph Prospecting

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Synopsis: The reflection prospecting method measures depths to subsurface strata by recording the travel time of reflected sound waves. The acoustic energy of the sound wave is converted into electrical energy by a pickup, amplified, filtered, and recorded. The equipment described provides automatic gain control in the amplifier, filtering to eliminate frequencies outside the reflection spectrum, and means of recording reflections from several points on the earth's surface, together with the necessary timing mechanism.

The Nature of Reflection Seismograph Prospecting

IN THE present-day search for petroleum, the reflection seismograph is an important and powerful tool. The apparatus used is predominantly electrical, and as such should be of interest to all electrical engineers, particularly those having an especial interest in the electronic and communication branches of electrical engineering.

Before considering the instruments used in reflection work, it is well to learn something of the purpose for which they are used. The principle of operation of the reflection seismograph is identical with that of the sonic depth finder. That is, depths to subsurface strata are calculated from the times required for sound waves to travel down to them and be reflected back to the surface. Reflection seismograph prospecting consists in thus measuring the depths of the various strata at many stations over a large area, mapping their folding and faulting in the hunt for likely traps for petroleum. The depths in which the geophysicist is interested range from a few hundred to 10,000 or 20,000 feet. Since the acoustic attenuation of earth is much greater than that of water, a sound wave of high initial amplitude must be transmitted in order that the reflected wave will be larger than the natural unrest of the earth's surface. This energy is usually released by exploding a charge of dynamite at the bottom of a hole drilled in the ground to a depth of 40 or 50 feet, with the charge covered with water or dirt. The charge is fired on a signal from the recording station, using special equipment which at the instant of explosion transmits a signal, known as the time of break, to the recording station.

The explosion of the charge starts a sound wave in the earth which is initially of roughly spherical wave front. As this wave front expands and passes through formations having various acoustic properties, it becomes distorted and part of its energy is reflected from and refracted at each interface between beds of differing velocities of propagation. Upon the arrival of the waves at the earth's surface, their acoustic energy is converted into electrical energy by a pickup, amplified, filtered, and recorded on an oscillograph, called in geophysical terminology a recording camera or simply camera. Also recorded are the time of break and timing lines.

Identification of Reflected Waves

In order to identify those waves which have suffered reflection, in the presence of refracted and direct disturbing waves, the practice is to record the arrival of the reflected waves at several different points in different directions and at different distances from the shot point. The distances are usually small compared to the depth from which it is desired to record reflections. Since the reflected wave front has a large radius of curvature (approximately twice the depth of the reflecting horizon) and usually arrives from almost directly below the recording station, it strikes the several pickups at almost the same time and the character of the movement of the surface will be nearly the same at all pickups. This sameness of appearance and arrival time is the chief criterion by which reflected waves are identified. Figure 1 shows a typical reflection-seismograph record. Six channels are used, the six pickups being placed in line with the shot point and 200 feet apart. At the point *A* is the time of break, when the charge was exploded. The first waves recorded on the lower six lines correspond to the arrival of the first disturbances of the earth's surface at the six pickups. The first wave on the uppermost trace is a direct wave because that pickup was very near the shot. On the other five the first wave arriving was refracted and traveled most of the way along the top of the first unweathered bed below the surface. In the region marked *B* the first identifiable reflection arrived. Other reflections are marked, the last marked *G*, arriving 2.323 seconds after the break, corresponding to a depth of approximately 10,150 feet.

From the record of figure 1 it is evident that a reflection is a transient disturbance and is therefore composed of waves of various frequencies. The predominant frequency of reflected waves generally ranges between 30 and 70 cycles per second. The frequencies of the major components of direct and refracted waves are, in general, below 30 cycles, and the frequencies of extraneous surface disturbances are usually higher than 70 cycles. It is usual practice to design reflection instruments to reject rather sharply frequencies below about 30 cycles, and to reject rather more broadly those above about 70 cycles.

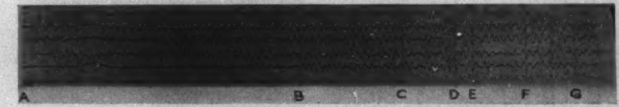

Figure 1. A six-channel reflection seismogram

The component parts of a typical reflection seismograph will be taken up in the order in which the waves pass through them. The first unit to be discussed will be the pickup.

Pickup

The most desirable pickup should be extremely rugged, light in weight, small, have a high sensitivity, and require very few connecting wires, these to be un-

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affected by water or weather conditions. Since one pickup would have difficulty in possessing all of these requirements, some compromises must be made. These compromises will have to be chosen with much care because a small change in one requirement may cause a larger change in some other. For instance, a high impedance mechanical-to-electrical converter may be small and light in weight, but it will eventually give trouble from electrical disturbances caused by leakage through insulation and contact resistance. A pickup should be rugged above all else, owing to the fact that time lost in the field is very expensive. A seismograph crew costs between $5,000 and $10,000 per month to operate, and when trouble appears the whole crew remains idle while one or two men make the repairs. The rough terrain traversed by a crew during a survey will certainly test any piece of apparatus for ruggedness.

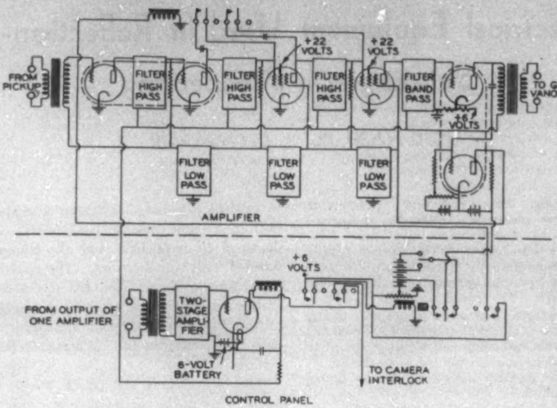


Figure 3. Schematic diagram of control panel and amplifier

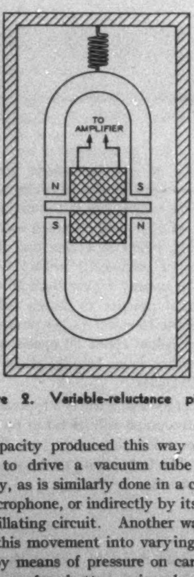


Figure 2. Variable-reluctance pickup

Practical reflection pickups, like nearly all earthquake seismographs, make use of the difference in movement or force between a suspended mass and its container resting on the earth. This movement is then converted into electrical energy in one of several ways. One method uses this movement to vary the separation of capacitor plates. The varying capacity produced this way can be made to drive a vacuum tube either directly, as is similarly done in a condenser microphone, or indirectly by its use in an oscillating circuit. Another way converts this movement into varying resistance by means of pressure on carbon as in the carbon-button microphone. In still another way, the piezoelectric effect of certain crystals is used to obtain this conversion. A mass is suspended on a crystal (usually Rochelle salt) and spring combination, thus flexing the crystal with movement of the earth. The magnetic induction method can be divided into two parts. One has a magnetic field of constant strength through which moves a coil of wire and the other a movable core which varies the reluctance of a magnetic circuit through which a coil of wire has been linked. The method most commonly used is the last one mentioned because its construction is simple, it can be made very rugged, and it has a reasonable sensitivity. Also, the output is proportional to the frequency of the ground motion, thus it acts as a filter and suppresses the low frequencies. This low-frequency discrimination may be moved up or down the frequency spectrum by corresponding changes of the natural frequency of the pickup. The natural frequency is usually made to fall in the range of the reflection frequencies. When this is done, it is necessary to overdamp the mechanical system to prevent the natural frequency from predominating on the record. Damping may be obtained electrically or mechanically. Mechanical damping is most common and consists of filling the pickup with oil of the proper viscosity to damp the movement to any degree desired. Of course, changes in temperature change the viscosity but it is not difficult to follow the seasons with the correct viscosity for each. The pickup shown in figure 2 uses permanent magnets as the mass and the coil wound on the core is designed to match a 200-ohm impedance line at 45 cycles per second. At 45 cycles per second, and an amplitude of 10^{-6} inches of ground movement, this pickup will deliver about 50 microvolts across a 200-ohm load.

Amplifier and Control Panel

The output of the individual pickups is led into the recording truck through multiconductor cables and terminated in an equal number of identical amplifiers. In addition, there is a main control panel from which the gain and frequency response of all amplifiers can be varied simultaneously. A schematic diagram of control panel and amplifier is shown in figure 3. A bank of 12 amplifiers with control panel ready for service is illustrated in figure 9.

The amplifier is probably the most important part of the reflection equipment. Its function is to amplify the output of the pickup to a sufficient level that rugged galvanometers may be used in the camera, to filter out undesired frequencies, and to so control the galvanometer deflections that the multiplicity of traces on the record may be compared over as large a part of the record as possible. The amplifier shown in figures 3 and 4 performs these tasks satisfactorily. It consists of five stages in cascade, followed by a rectifier. The first two stages are high-mu triodes, the third and fourth are remote-cutoff pentodes, the fifth stage is a triode output tube, and the rectifier is an over-biased triode. The output stage is coupled both to the rectifier grid and to an output transformer matching the low-impedance galvanometer. The rectifier output is filtered by a multisection filter and the resulting direct voltage is im-

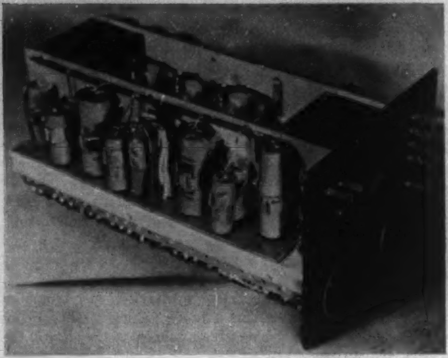


Figure 4. Reflection seismograph amplifier

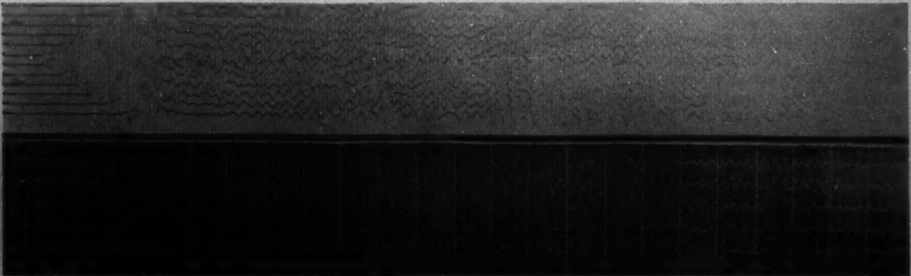
pressed as a negative bias on the grids of the first four tubes. The maximum over-all voltage gain at 45 cycles from first grid to primary of the output transformer is approximately 315,000 times (110 decibels). The application of 17 volts negative bias by the rectifier system reduces the over-all gain to 10 times (20 decibels). Distortion in the output is negligible for voltages below 0.05 volts root-mean-square on the input grid. The output voltage increases only about 20 per cent when the voltage on the input grid is increased from 5 microvolts to 50,000 microvolts (80 decibels).

The design of a single-sided amplifier to meet these specifications is a rather involved process, but it is considerably simplified by the fact that in general the amplitude of the voltage input to the amplifier decreases with time in approximately an exponential fashion after the initial disturbance, or "first kick," arrives. These first kicks are useful in the computation of the data on the record, and it is desirable to record them clearly. They are often characterized by a very gradual onset, the apparent frequency varying continuously from zero up to some high value over the first half cycle. In order to record this kind of wave form, it is necessary that the amplifier have less low-frequency filtering at the time of arrival of the first kicks than is desirable for the recording of reflections. Also, it is desirable that the first kicks be recorded on a very quiet trace, in order that the time of onset may be determined to within 0.001 second. This is possible because the first kicks are much stronger than the subsequent reflections. These desires are attained through the use of a system of relays. Each amplifier contains a multipole relay which bypasses a large part of the low-frequency filter network. These relays are actuated by one of the first kicks through an auxiliary amplifier, a vacuum-tube relay, and a master relay, all incorporated in the main control panel. The vacuum-tube relay is a lock-up relay, interlocked with the recording camera so that it locks only when the recording camera is in operation. This prevents premature operation and locking from accidental disturbances, such as persons walking near the pickups, etc. This locking relay energizes a slow-acting master relay. The master relay is adjusted for a delay of 0.25 second in order that one of the pickups near the shot point may be used for actuating the relay system. This is desirable because the first kicks on the near pickups are much stronger than those on the pickups farther from the shot point. The operation of the master relay releases the individual amplifier relays, which fall out and remove the by-passes from the low-frequency filters. Another set of contacts on the master relay changes the bias on the amplifier tubes from a high negative value to a low one. The initial bias is adjustable and controls the sensitivity to first kicks. The final bias is fixed at the value which gives maximum amplifier gain. The use of a high initial bias provides quiet traces on which to record first kicks, and also prevents motorboating of the amplifiers when their low-frequency response is extended by the by-pass networks.

Filtering

A very important consideration in the design of a reflection amplifier is the degree of low-frequency filtering desirable. It must be borne in mind that reflection equipment is primarily intended to record a succession of transient waves in such a manner that they may be identified with the maximum of certainty. In particular, it is desirable that the first part of the wave be identifiable. The application of low-frequency filtering tends to minimize the first part of a reflection, but in many cases a considerable degree of such filtering is necessary in order to pick out any reflections at all. In most cases the beginning of the reflection is not sharp enough to pick reliably. Instead, an upward or downward peak is picked. Since a change in the amount of filtering changes the phase characteristic, the

Figure 5. Twelve-channel record using automatic gain control, moving-coil galvanometers and shutter fork, and six-channel record using fixed gain, string galvanometer, and synchronous-motor timer



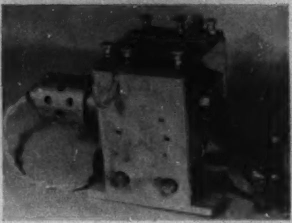


Figure 6. Six-element string galvanometer and single-element moving-coil galvanometer

times at which the peak is recorded will change. Thus records taken at the same place, but with different amounts of filtering, will record reflections at different times. Since it is desirable to correlate reflections at many points when prospecting an area, records at all points should be made with identical instruments. This makes it necessary to decide on the use of a certain degree of filtering which will give satisfactory records in the great majority of cases, compromising on the basis of past experience between elimination of undesired low frequencies and loss of reflection character.

Faithful response to transient waves of varying frequency requires that all filter networks be damped to a high degree. High damping, that is, near critical or beyond, in turn requires a greater number of filter sections to give the desired frequency response. Now a multisection damped network acts somewhat like a network having fewer meshes and less damping. Also the matter of size and weight becomes important. Thus some compromise is necessary in practical design. There has been some argument concerning the comparative merits of an underdamped filter of few sections and an overdamped filter having the proper number of sections to give approximately the same frequency response. There is no doubt that some degree of intentional damping is necessary, but it is sometimes difficult to decide what degree of damping and number of filter sections give the most satisfactory records.

Another solution to the problem of elimination of low-frequency waves is offered by the fact that these waves arrive at different distances from the shot point much farther out of phase than reflected waves. Thus if an amplifier is connected not to one pickup, but to several, at various distances from the shot point, reflected waves will be reinforced and other waves will be cancelled to some extent. Another method is to feed part of the signal in each amplifier to its adjacent amplifiers. These methods give directional characteristics to the system, which is just what is desired, as reflections generally arrive from almost directly below the instruments. The degree of elimination of undesired waves which may be thus obtained is sometimes astounding. Consequently, less filtering may be used, with corresponding improvement in reflection wave form.

Amplitude Control

The frequency response of the amplifier having been decided upon, there remains another problem to be solved. This may be called the amplitude response. Since the movement of the earth, and hence the output of the pickups, due to the shot is much greater for first kicks and shallow reflections than for deeper reflections, the use of a recording system having fixed sensitivity would permit the use of only a small portion of the record. This would require several records with different explosive charges or different instrument sensitivities in order to record all the desired reflections with usable amplitudes. Also, each time the equipment is moved to another shot point the sensitivity of the individual channels must be adjusted by means of trial shots to compensate for local irregularities in the transmission characteristics of the earth. This causes undesirable expenditures of time and material.

The incorporation of automatic gain control in the amplifiers remedies both of these evils. The use of automatic control is possible because in the case of the great majority of shots, the amplitude of the envelope of the voltage output of the pickup varies slowly compared with the frequency of the waves to be recorded. These waves are transient disturbances of continually changing frequency and amplitude and of only a few cycles duration. Since it is desirable that the general shape of these transients be retained, the gain-controlling mechanism must not respond instantaneously to changes in amplitude. Most satisfactory results are obtained when it responds more rapidly to increases in amplitude than to decreases. This makes the amplitude at any part of the record somewhat dependent on preceding amplitude, but if the rate of change of response to decreases in amplitude is made somewhat faster than the general rate of decay of the envelope of the pickup output very satisfactory control is obtained. Figure 5 illustrates records obtained with and without automatic gain control.

The means by which amplitude control is obtained are described below.

As before mentioned, each amplifier contains a triode rectifier. The grid of this rectifier is coupled to the plate of the output tube and its grid bias is continuously adjustable from zero to -22 volts. The value of this bias determines the a-c output voltage at which the rectifier begins to pass current, and thus the upper limit of the output voltage. Plate voltage for the rectifier is supplied by a battery, common to all amplifiers.

The negative bias developed across the load resistor of the rectifier is filtered and applied to the fourth-stage control grid, further filtered, and applied to the third-stage control grid. An adjustable portion of the third-stage bias is applied to the grids of the first and second stages. This permits some adjustment of the initial sensitivity of individual amplifiers to compensate for decreasing first-kick amplitude with increasing distance from the shot point. At the same time it allows the use of unmatched tubes in the first two stages. For input voltages of the order of those handled by reflection amplifiers, the over-all gain of the first two stages may be changed by as much as 50 to one by variation of grid bias with negligible distortion.

The second and third stages use remote-cutoff pentodes because of their superior voltage-handling ability. Control bias is applied to both control and suppressor grids of both tubes, but the bias rarely be-

Figure 7. Fork-driven synchronous-motor timer

comes high enough for the suppressor grid to have much control of the tube gain. Screen voltage is obtained from a voltage divider across the plate-voltage supply. The use of a series dropping resistor for screen supply extends the cutoff characteristic considerably but requires the development of several times as much bias voltage as is required when a voltage divider is used. Some compromise is necessary between a choice of a very remote-cutoff tube, with its low distortion, and a sharper-cutoff tube, with its better control of output voltage. The use of tubes of the so-called "mixer" types, namely where the signal is applied to one grid and the control bias to another, gives very good control action but poor voltage-handling ability, and considerable difficulty is experienced in matching these tubes even within broad limits.

Recording Camera

The output of each amplifier is connected to the recording oscillograph by which a record is made of the ground motion that excited the pickups. This record is usually made on sensitized paper, which varies in width from about two inches to ten inches, depending upon the number of pickup stations used. The length of the record depends upon the greatest depth of the stratum from which reflections are desired and upon the speed at which the paper is driven. The average length of record is about four feet. Each pickup station makes one trace on the record, with each amplifier driving one unit of a galvanometer. The galvanometer may be the string type or the moving-coil-and-mirror type. The string galvanometer is nearly always a multiple unit of six or more strings as shown on the left-side of figure 6. This galvanometer is rather large in size because it requires an electromagnetic field. The strings occupy a space of about one-half inch or less in width and their movements are magnified optically with lenses. This means that it is rather difficult to focus all of the strings equally across the flat record. Also the deflection of the strings is not linear and with a large movement as usually happens when the first shock strikes the pickup, the strings interfere and sometimes tangle with each other. Since the illumination for this type of galvanometer is transmitted from the back, the strings appear as shadows on the paper. This gives white traces on a dark background, and such records are very tiring to the eyes of the computers.

The d'Arsonval galvanometer, on the other hand, uses a tiny mirror on a rotating coil to reflect a spot of light to the sensitized paper. This gives a black trace on a white background. One of these galvanometers is shown on the right side of figure 6. These galvanometers give an almost linear reproduction of the amplifier output since they are placed almost directly in front of the trace they are exposing on the record. They are rugged in construction and, since a coil of a large number of turns may be used as the moving element, the sensitivity is 25 or more times that of the string galvanometer even with the use of small permanent magnets. Of course, the moving-coil construction does not respond to high frequencies, but this is a desirable characteristic. High frequencies found at the pickup are usually noise, wind, or other movements not desired on the record. These galvanometer units may be added or subtracted from an oscillograph making for more flexibility. The difficulties found with them are mostly in the mirror. If a large mirror is used, there is much trouble from distortion of the glass, but, if it is small, not enough light is reflected to expose the record properly. A complete recording camera is illustrated in figure 10.

Timing

When the charge of dynamite in the hole at the shot point is exploded, the electrical circuit to the cap is broken. This interrupts the current that was flowing in the cap line just previously and permits the collapse of the magnetic flux in a transformer carrying this current. The electrical impulse produced is sent by radio or wire to the recording oscillograph where it deflects one of the galvanometers. The galvanometer used may be a separate one or the impulse may be composited on one that is later to record the ground motion. This time of break, as was mentioned earlier, is zero on the record. Now in order to find the elapsed time to the reflections it is necessary to have time marks on the record. Time marks are lines exposed across the record at right angles to the galvanometer traces and ordinarily are spaced 0.01 second apart. Sometimes a distinction is made in the line representing 0.1 second, making more convenient the counting of time on the record. A tuning fork of usually two tines, but sometimes one, is almost universally used for obtaining these time lines. One method, a well-known system, uses an electromagnetically driven fork that interrupts an electric current at 50 cycles per second to drive a small synchronous motor and paddle wheel. Such a unit is shown in figure 7. With this method the 0.01- and 0.1-second time lines are easy to obtain by making each tenth spoke a little wider than the others. But otherwise this piece of equipment is too heavy and large and frequently gives feedover by induction from the motor windings. Also, the fork contacts burn and get out of adjustment. The other

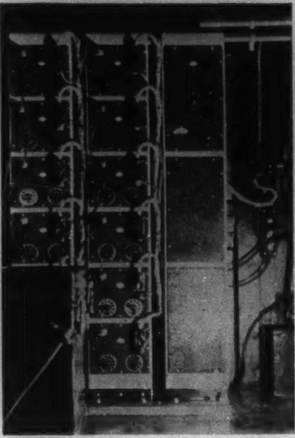


Figure 9. Twelve-channel reflection seismograph amplifier bank set up in truck

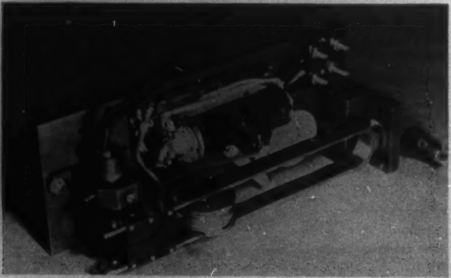


Figure 8. Shutter fork timer

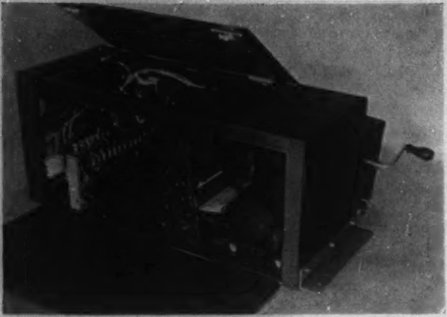


Figure 10. Fourteen-element recording camera

common method of timing makes use of a shutter interrupting a light beam to flash a mark across the record at 0.01-second intervals. This shutter is ordinarily mounted on a fork of one or two tines and the fork started by one pulse from an electromagnet and permitted to decay at will. It will continue to vibrate at a good amplitude long enough to obtain the usual record of three or four seconds duration. This timing unit is shown in figure 8 and by comparison with figure 7, it can be seen to be more compact, much smaller in size, and relatively foolproof.

Paper Drive

The number of records taken during a day's work depends almost entirely upon the kind of country being surveyed. If the shot holes are difficult to load or the country so rough or wet that much time is required to move, 12 records may represent a hard day's work. The average of good and bad days is about 40 records with about five feet of sensitized paper used for each, including some waste on each end of the record. It is common practice to use a supply roll of this paper and cut off and develop each record as it is taken. The driving mechanism for the paper consists of a motor, either electric or spring with a governor control, and a friction roller or a reel. The friction-roller drive is probably the better, owing to the fact that the paper speed is constant and therefore the time lines will be equally spaced, but the reel drive is easier to build and is more foolproof. In the friction-drive method the paper is fed between two rollers driven by the motor, thus feeding the paper at the peripheral speed of the rollers. In the reel method, the paper is attached to a spool driven by the motor and the paper wound on the spool in a number of layers. This means that the speed of the paper is a function of the length of the record. If the records in the latter case are started at about the same time, the time lines on all of them will be spaced approximately equally and the records may be compared easily.

Discussion

E. E. George (Tennessee Electric Power Company, Chattanooga): This paper is extremely interesting, especially in its description of the development of very sensitive and accurate measuring equipment suitable for rough handling in the field. The construction of an amplifier with 110 decibels gain for this service is particularly interesting. Apparently no use is made of feedback. While this would necessitate increased amplification it would add to stability and fidelity. It might also be possible to place filter circuits in the feed-back path and secure additional discrimination.

Many engineers would probably be interested in some of the selections of equipment for the severe service required of portable devices. For instance, are glass or metal tubes used? Are the tubes of the same type used in radio receivers, or are they of special types such as the 1620, 1621, and 1622? Has any use been made of the special types of tubes developed for train-control service or for telephone repeater applications where long life and reliability are of particular importance? Is the type of oscillograph used similar to that used by power companies? What type of power supply is used on the recording trucks?

The authors should be congratulated on presenting in such an interesting fashion a special industrial application of electronic equipment. It is apparent that the design has required an enormous amount of development work. It is to be hoped that the Institute will arrange for more papers on industrial applications of electronic devices, particularly in instances like this which are absolutely new to the average electrical engineer.

C. C. Nash, Jr., and **C. C. Palmer:** In the instruments described little use is made of inverse feed back, because of the greater number of parts required. Some experimental work has been done with amplifiers using feedback with filter networks in the feed-back path as suggested by Mr. George.

The equipment described uses ordinary glass radio receiving tubes throughout. The glass tubes have given more reliable service than metal ones. For this service there seems to be very little difference in the service life of ordinary radio tubes and special long-life tubes.

The oscillograph is not radically different from those used by power companies.

Batteries are usually used to supply power to the instruments, storage batteries being used for amplifier heater power and dry batteries for plate power. Some use has been made of motor generators and vibrator units for plate supply. Storage batteries are used to light the oscillograph lamps and to supply power to the paper-driving motor. A recording truck usually contains four or five heavy-duty storage batteries. These batteries are charged by heavy-duty automotive generators belted to the truck engine.

Harmonics in the A-C Circuits of Grid-Controlled Rectifiers and Inverters

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Synopsis: This paper summarizes the results of an investigation of the harmonic currents and voltages in the a-c circuits of grid-controlled rectifiers and inverters. The principal part of the paper presents the development of a theoretical method for predetermining the magnitude of the harmonics in terms of the d-c load current, the commutating reactance, the rectifier transformer secondary voltage, and the amount of grid control. Harmonic voltages in the supply circuit may then be calculated from the harmonic currents and the supply-circuit reactances at the various harmonic frequencies.

General curves are given to facilitate the calculation of the harmonic currents for the range of conditions usually encountered. In addition, curves are included for the easy determination of the product of the supply-circuit current and its own telephone influence factor, the *I·T* product, which quantity is useful in inductive co-ordination studies. Comparisons are given between the results of tests and the results of calculations by the theoretical method presented in this paper. These and other comparisons show very satisfactory checks so that the method may be considered to be established.

The case of the inverter is treated in a manner similar to that used for the grid-controlled rectifier. The general curves for the rectifier may also be applied to the inverter by appropriate choice of the defining angles.

The case of a-c circuits with nonlinear frequency-reactance characteristics is briefly considered, and an empirical modification of the theoretical method is suggested. This modification may be applied to the case of a rectifier provided with a-c filtering equipment. The wave forms of current and voltage in one such supply circuit were obtained from oscillograms. A comparison of these oscillograms shows the great improvement in wave form which may be accomplished by the addition of filters.

A WELL-KNOWN property of all rectifier- and inverter-type apparatus is that they produce harmonic distortions in both the current and voltage wave shapes on both the supply and output circuits. Several investigators have made contributions to the problem of determining these harmonic voltages and currents under various conditions of rectifier operation. There are four distinct steps in this development which are:

1. D-c harmonics without grid control.
2. D-c harmonics with grid control.
3. A-c harmonics without grid control.
4. A-c harmonics with grid control.

These will be reviewed briefly in order to show the relation of the present investigation to that of previous work.

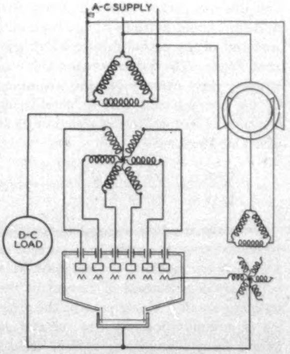

Figure 1. Schematic diagram of six-phase star grid-controlled rectifier

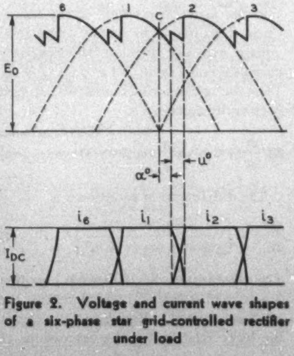

Figure 2. Voltage and current wave shapes of a six-phase star grid-controlled rectifier under load

Harmonics on the d-c side of a rectifier are commonly determined on the basis of an "internal harmonic voltage" whose magnitude may be expressed as a function of the output current, angle of overlap, and amount of grid control. The harmonic currents in the d-c load circuit may then be computed from the harmonic voltages and the d-c load circuit constants including the "internal inductance" of the rectifier. The internal harmonic voltages are estimated by a theoretical method assuming an infinitely high inductance in the d-c load circuit. The formulas for the case of a rectifier without control grids have been given by several authors, for example, Prince and Vogdes,[1] and Marti and Winograd.[2] Recently the corresponding case for grid-controlled rectifiers has been analyzed by Stebbins and Frick,[3] who have extended the previous theoretical method to cover the range of grid control.

Harmonics on the a-c side of rectifiers without control grids may be estimated either by empirical or by theoretical methods. In the empirical method developed by Blye and Kent,[4] the harmonic currents are considered as being caused by internal harmonic voltages acting on the harmonic impedances of the supply system and a fictitious resistance varying with the load. The theoretical method for rectifiers without control grids, presented by Brown and Smith,[5] assumes (1) an inductive supply circuit through which commutation takes place, and (2) a constant output current due to infinitely high inductance in the load circuit. Using these assumptions, analytical expressions are derived for the anode currents which have a "flat top" wave form except during the commutating period when the current is transferred from the outgoing anode to the incoming anode in accordance with the voltage available for circulating the current through the inductance of the commutating circuit. The harmonic voltages in the supply system may then be computed on the basis of the voltage drops due to the harmonic currents flowing through the various circuit elements, considering the rectifier as the source of these harmonic currents.

The fourth step is given in this paper which presents a theoretical method for estimating harmonic currents and voltages in the supply circuits of grid-controlled rectifiers. It may be viewed as a generalization of the theoretical method for rectifiers without control grids.

The determination of harmonic currents and voltages in the a-c and d-c

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1. For all numbered references, see list at end of paper.

circuits of inverters is a problem which has received relatively little attention in the technical literature. However, the harmonic problem in the inverter is closely allied to the problem in the grid-controlled rectifier, and the same theoretical methods of analysis may be applied. In fact, the solution of the grid-controlled rectifier may be applied to the inverter provided appropriate choice is made of the angles corresponding to the angles of overlap and retardation for the rectifier.

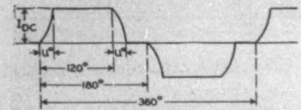

Figure 3. Line-current wave shape in primary of six-phase star grid-controlled rectifier under load

Determination of Harmonic Currents and Voltages From Theoretical Wave Shape Under Load

Consider a grid-controlled rectifier supplied from a six-phase star-connected transformer as shown in figure 1. Assume that the output circuit is of infinitely high inductance so that the output current may be taken as constant. Assume that the impedances of the supply circuit vary linearly with frequency so that they correspond to those of a simple inductance. Assume also that the rectifier is fully symmetrical in all phases so that the harmonic voltage and current waves are identical in the different phases.

On the basis of the foregoing assumptions, it is possible to prepare the diagram of figure 2 in accordance with conventional rectifier theory. Figure 2 applies to the condition for the transfer of current from anode to anode. The secondary crest voltage is E_0 and the constant value of d-c load current is I_{dc}. The angle of retardation and the angle of overlap are shown by the symbols α and u respectively. The voltage and current for any particular anode are designated with the arabic numeral subscripts from 1 to 6. In an ordinary rectifier, anode 1 would carry current to the point c but with energized grids commutation would be delayed by the angle α. Commutation lasts through a period corresponding to the angle u. In this interval the current is transferred from anode 1 to anode 2 as shown in the diagram. After 60 electrical degrees or $\pi/3$ radians, anode 3 begins to carry current and the commutation is identical with that of the previous pair of anodes. The line current on the primary side, shown in figure 3, consists of currents supplied from two adjacent anodes, such as anodes 1 and 2 of figure 2, assuming the transformer delta voltage is equal to the secondary star voltage.

The magnitude of the anode current is:

$$I = E_0 \frac{\sin \frac{\pi}{p}}{X} [\cos \alpha - \cos (u + \alpha)] \qquad (1)$$

where p is the number of phases in each secondary phase group of the rectifier. The total d-c current for a phase group is given by the above expression which for the particular case of the six-phase rectifier shown in figure 1 is the same as the output current.

The shape of the anode-current wave thus includes (1) a "flat top" wave during the principal part of the conducting period and (2) curved portions at the beginning and end of the period during which current flows. The instantaneous value of primary line current for the beginning of the commutating period, considering the start of current flow at zero time, is as given by Herskind:[6]

$$i = I \left[\frac{\cos \alpha - \cos (\theta + \alpha)}{\cos \alpha - \cos (u + \alpha)}\right] \qquad (2)$$

Since the d-c load current is assumed to be constant, the increase in current in the incoming anode is accompanied by a corresponding decrease of current in the outgoing anode. Consequently, the process of commutation may be viewed as arising from a circulating current caused by the voltage available in the circuit acting through the circuit inductance. The total circuit inductance is twice the commutating inductance since by definition the latter is one-half of the inductance from anode to anode. The total voltage available to cause the circulating current is equal to $2E_0 \sin \pi/p \sin (\theta + \alpha)$. Thus the relation which must be satisfied is given by equation 3.

$$2L \frac{di}{dt} = 2E_0 \sin \frac{\pi}{p} \sin (\theta + \alpha) \qquad (3)$$

The differential of equation 2 is

$$\frac{di}{dt} = I \left[\frac{\omega \sin (\theta + \alpha)}{\cos \alpha - \cos (u + \alpha)}\right] \qquad (4)$$

The substitution of equation 4 in equation 3 results in equation 1 which verifies the relation assumed. Equation 2 thus gives the basic relation for the expressions of current during the commutating period.

Equation 2 gives the current for the beginning of flow in the incoming anode, but it is obvious that the same relation can also be used for current in the outgoing anode, since the sum of the currents in these two anodes is equal to the output current. Similarly, the expressions for current flow at other commutating periods may be expressed if correction is made in the angles defining the commutating period in that particular pair of anodes. Referring to figure 3, it becomes possible with the aid of equation 2 to write an analytical expression for the current wave form. This leads to the result given in table I for 0 to π radians covering one-half cycle of the a-c wave. It may be shown that the following half cycle is of identical wave shape.

With an analytical expression for the current wave for a half cycle, it is possible to carry out a Fourier expansion with the individual harmonic currents given by the following relations:

$$m = \begin{bmatrix} a_1 \sin \theta + a_5 \sin 5\theta + a_7 \sin 7\theta + \\ a_{11} \sin 11\theta + \ldots \\ b_1 \cos \theta + b_5 \cos 5\theta + b_7 \cos 7\theta + \\ b_{11} \cos 11\theta + \ldots \end{bmatrix} \qquad (5)$$

The solution of the Fourier expansion is given by the following:

$$a_m = \frac{4I}{\pi}\left[\frac{+ P_m \sin \frac{\pi m}{3} + Q_m \cos \frac{\pi m}{3}}{m (m^2 - 1) [\cos \alpha - \cos (u + \alpha)]}\right] \times \sin \frac{\pi m}{3} \qquad (6)$$

$$b_m = \frac{4I}{\pi}\left[\frac{+ Q_m \sin \frac{\pi m}{3} - P_m \cos \frac{\pi m}{3}}{m (m^2 - 1) [\cos \alpha - \cos (u + \alpha)]}\right] \times \sin \frac{\pi m}{3} \qquad (7)$$

where P_m and Q_m are expressed as follows:

$$P_m = m \sin (u + \alpha) \cos mu - \cos (u + \alpha) \sin mu - m \sin \alpha \qquad (8)$$

$$Q_m = m \sin (u + \alpha) \sin mu + \cos (u + \alpha) \cos mu - \cos \alpha \qquad (9)$$

The root-mean-square value of the individual harmonic current is given by equation 10.

$$I_m = \frac{\sqrt{a_m^2 + b_m^2}}{\sqrt{2}} = \frac{2\sqrt{2}I}{\pi} \times \left[\frac{\sqrt{P_m^2 + Q_m^2} \sin \frac{\pi m}{3}}{m(m^2 - 1)[\cos \alpha - \cos (u + \alpha)]}\right] \qquad (10)$$

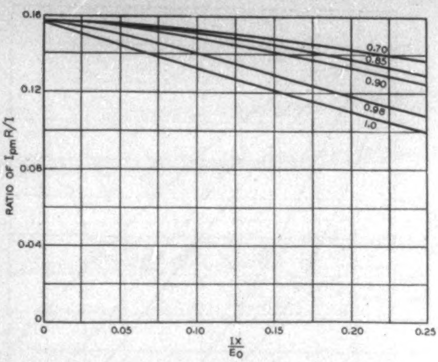

Figure 4. Fifth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

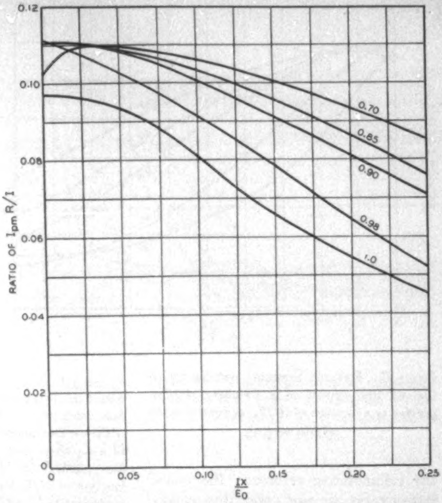

Figure 5 (right). Seventh harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

The terms a_m and b_m, being respectively the sine and cosine components of the harmonic expansion, permit the determination of the phase angle which may be expressed in terms of the angle at which maximum value is reached with respect to zero time, which angle is expressed as follows:

$$\theta_H = -\frac{\pi m}{3} - \tan^{-1}\frac{Q_m}{P_m} \text{ radians} \qquad (11)$$

The formulas for a_m and b_m do not apply to the fundamental because the expressions of equations 6 and 7 become indeterminate. It is necessary, therefore, to compute the components of the fundamental separately and this has been done with the following results:

$$a_1 = \frac{\sqrt{3}I}{2\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right] \times \left\{\begin{array}{l}\cos\alpha\,[+\sin^2 u - \sqrt{3}(u - \sin u\cos u)] \\ +\sin\alpha[-\sqrt{3}\sin^2 u + u + \sin u\cos u]\end{array}\right\} \qquad (12)$$

$$b_1 = \frac{\sqrt{3}I}{2\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right] \times \left\{\begin{array}{l}+\cos\alpha[\sqrt{3}\sin^2 u + (u - \sin u\cos u)] \\ +\sin\alpha[\sin^2 u + \sqrt{3}(u + \sin u\cos u)]\end{array}\right\} \qquad (13)$$

The root-mean-square value of the fundamental is given in equation 14.

$$I_1 = \frac{\sqrt{3}I}{\sqrt{2}\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right] \times \left\{\begin{array}{r}\sqrt{u^2 - 2u\sin u\cos u\cos 2\alpha + \sin^2 u} \\ + 2u\sin u\sqrt{\cos\alpha\sin\alpha}\end{array}\right\} \qquad (14)$$

Examination of the above expressions for the harmonic and fundamental components of the a-c wave will show that for the condition of a rectifier without control grids for which $\alpha = 0$, the expressions reduce to a form identical with that given by Brown and Smith.[5]

While the above expressions have been derived on the basis of a 6-phase rectifier, the same expansion with appropriate multipliers may be used for double three-phase rectifiers. In addition, it is possible to apply the same expansions to 12-phase rectifiers operating with similar connections it the harmonics of the series which includes the 5th, 7th, 17th, 19th, 29th, 31st, etc., are considered to be reduced theoretically to zero and actually to 25 per cent of their 6-phase magnitudes to account for values encountered under practical operating conditions. This factor of 25 per cent for the harmonics of this series is empirical but is based on the values recommended in the Edison Electric Institute report on "Rectifier Wave Shape."[7]

General Curves for Determination of Harmonics

The analytical solution for the root-mean-square magnitude of the individual harmonic currents given by equation 10 is rather tedious for practical use. Accordingly, the results have been expressed in graphical form* by means of figures 4 to 13 inclusive. For the application of these curves, it is necessary to obtain for any particular rectifier merely the d-c load current for an anode group,

Table I. Analytical Expression for Anode Current

Part	Range in Radians	i
a	$0 < \theta < u$	$\frac{\cos\alpha - \cos(\theta+\alpha)}{\cos\alpha - \cos(u+\alpha)} I$
b	$u < \theta < 2\frac{\pi}{3}$	I
c	$2\frac{\pi}{3} < \theta < \left(2\frac{\pi}{3} + u\right)$	$\frac{\cos\left(\theta + \alpha - 2\frac{\pi}{3}\right) - \cos(u+\alpha)}{\cos\alpha - \cos(u+\alpha)} I$
d	$\left(2\frac{\pi}{3} + u\right) < \theta < \pi$	0

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* Since this paper was submitted to the Institute the authors' attention has been called to "The Mercury-Arc Rectifier Considered in Relation to the Power-Supply System; An Analysis of Its Operation," by P. G. Laurent, *R.G.E.*, volume 44, number 2, pages 47–60, July 9, 1938. The scope of this article is quite different from that of the present paper; however, it does include certain general curves which although of restricted range are similar in form to those presented in this section.

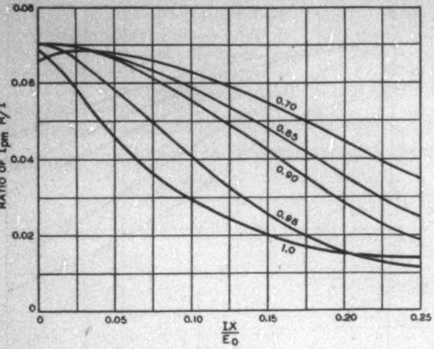


Figure 6. Eleventh harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E₀ for several ratios of grid control

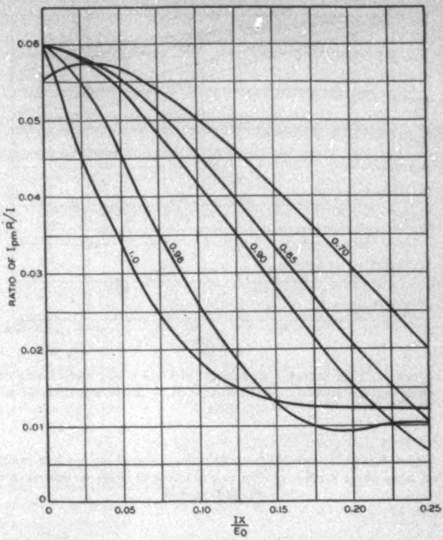


Figure 7. Thirteenth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E₀ for several ratios of grid control

the commutating reactance, the transformer ratio, the crest value of secondary voltage, and the amount of grid control. The last named may be defined as cos α which is the ratio of the d-c circuit voltage with grid control to the voltage without grid control, other conditions remaining the same. These curves give a factor which is equal to the ratio of the harmonic current in the supply line to the direct current per secondary phase group, provided the line-to-neutral voltages on the primary and secondary sides are equal. If the actual ratio of primary to secondary voltages-to-neutral is R, the root-mean-square value of the harmonic current in the supply circuit becomes

$$I_{pm} = \frac{KI_{\text{dc}}}{2R} = \frac{KI}{R} \ldots \text{6-phase from double-wye with interphase transformer} \qquad (15)$$

$$I_{pm} = \frac{0.483KI_{\text{dc}}}{R} = \frac{1.932KI}{R} \ldots \text{12-phase from quadruple-wye with interphase transformers} \qquad (16)$$

where K is the factor obtained from the Fourier analysis. This factor is the ratio $I_{pm}R/I$ which is plotted in figure 4 to figure 13 inclusive.

The general curves for the determination of harmonic currents apply to the common types of 6- and 12-phase con-

Figure 8. Seventeenth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E₀ for several ratios of grid control

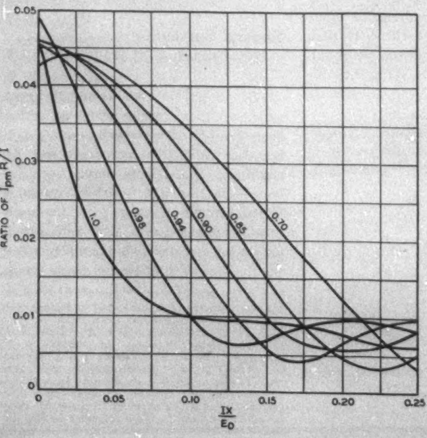
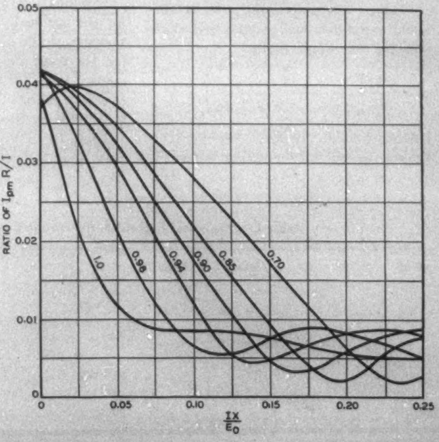


Figure 9. Nineteenth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E₀ for several ratios of grid control



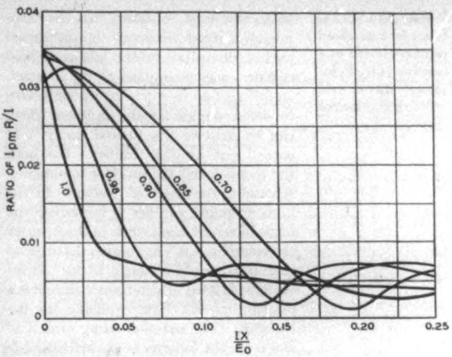


Figure 10. Twenty-third harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

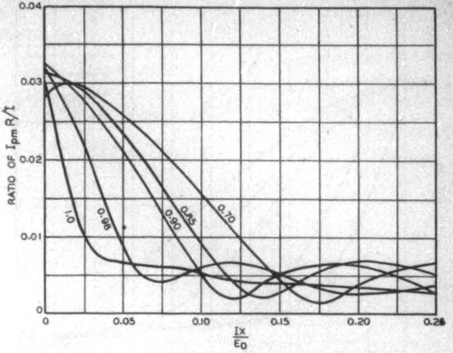


Figure 11. Twenty-fifth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

nections of power rectifiers. These curves may also be applied to other connections, provided the sum of the angles u and α is not greater than 41 degrees for $p = 6$ and 20 degrees for $p = 12$. This limitation is necessary to avoid the condition for which an additional anode begins to carry current in the rectifier with the larger number of phases.

Comparison With Test Results

The accuracy of the theoretical method just described for estimating harmonic currents in the supply circuits of grid-controlled rectifiers, is best shown by comparison with the results of harmonic measurements made during actual operation. Table II gives a comparison of test and theoretical values for four different conditions of rectifier load and ratios of grid control. It will be noted that exceptionally good checks are obtained. The last three columns on the right-hand side of table II apply to the rectifier operating without grid control. A comparison can thus be made between tests, and calculations by both the theoretical and empirical methods previously discussed. On the whole, the theoretical method gives in this case somewhat closer checks than the empirical method. Table III gives a similar comparison for another rectifier for a wider range of load and wider range of grid control.

It will be noted that the theoretical

Figure 12. Twenty-ninth harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

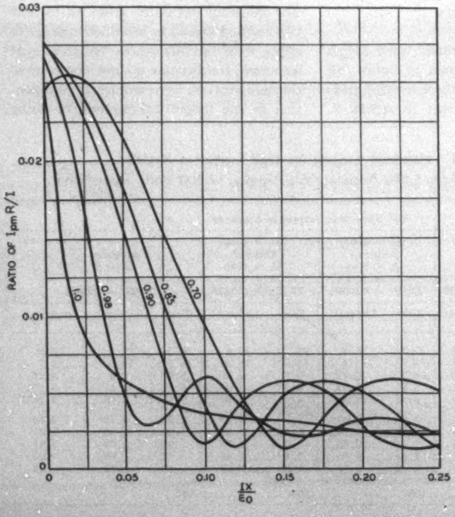
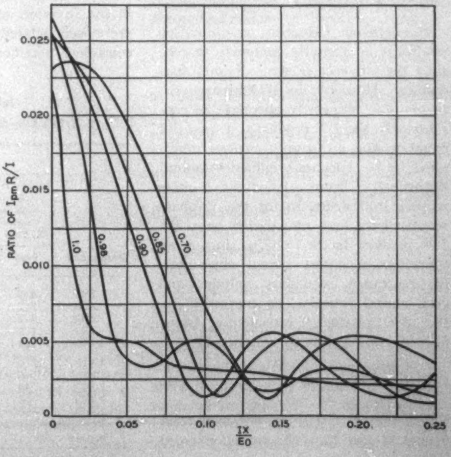


Figure 13. Thirty-first harmonic component of the a-c line current of a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control



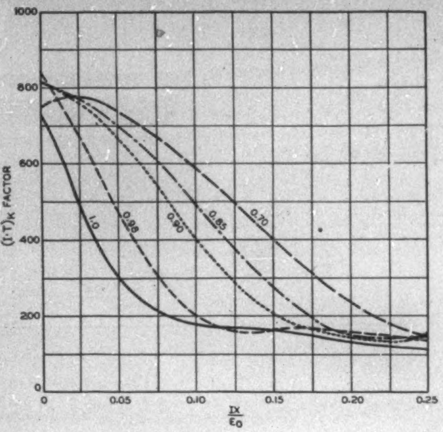


Figure 14. $(I \cdot T)_k$ factor for a six-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control

method gives very satisfactory comparisons with tests for a wide range of loads and grid control ratios. The comparisons in table II are better than those of table III because in the former tabulation the tests were made on a system whose supply-circuit reactance varied linearly from 60 to 2,000 cycles, and in this respect conformed more closely to one of the basic assumptions of the theoretical method.

It will be noted that the harmonic distortions for grid-controlled rectifiers may be appreciably greater than those for rectifiers without control grids. This ratio for certain values of grid control and load may be as great as four to one.

I·T Product Curves

In detailed inductive co-ordination studies it is generally necessary to consider the influence of the individual harmonics. However, in preliminary estimates it is frequently adequate to consider only the $I \cdot T$ product; a quantity equal to the a-c supply current multiplied by its telephone influence factor.[8] Accordingly, figure 14 for the 6-phase rectifier and figure 15 for the 12-phase rectifier have been prepared to show the $I \cdot T$ product factor, $(I \cdot T)_k$, for given conditions of output current, commutating reactance, secondary voltage, and grid control ratios. The expression for the $I \cdot T$ product, considering transformer ratio, is given by equation 17.

$$I \cdot T = \frac{(I \cdot T)_k I}{R} \tag{17}$$

where factor $(I \cdot T)_k$ is obtained from figures 14 and 15. The curves given in figure 15 for the 12-phase rectifier are obtained from harmonic currents for the 6-phase rectifier plotted in figures 4 to 15 inclusive, but with the 5th, 7th, 17th, 19th, 29th, and 31st harmonics reduced to 25 per cent of their 6-phase magnitudes. This factor of 25 per cent, as mentioned previously, is empirical but is based on the recommendations of the EEI report on "Rectifier Wave Shape."[7] It should be pointed out that these curves can be used only where the impedance of the supply circuit is linear with frequency.

Application of Theoretical Method to Inverters

The voltage and current wave forms in the inverter, as shown in figure 16, are closely related to those of the grid-controlled rectifier shown in figure 2. In fact, it may be shown that the theoretical method discussed in an earlier part of this paper for the grid-controlled rectifier, may be applied to the inverter. In order to do this it is merely necessary to define angles for the inverter which can be used in the Fourier analysis as carried out for the rectifier. For both the rectifier and the inverter the angle u represents the angle of overlap. In the grid-controlled rectifier α represents the angle of retardation, while in the inverter the angle $(u + \alpha')$ represents the angle of grid advance. The angle α' for the inverter is in itself of significance since it is a measure of the time available for deionizing. The notation using angles α' and u for the inverter is of particular advantage in the study of the harmonic problem, since its adoption permits the use of the exact formulas derived for the grid-controlled rectifier by the mere substitution of these values for α and u respectively. The general curves of figures 4 to 15 inclusive may also be applied to the inverter by the substitution of the corresponding quantities for the inverter, being careful to use cos α' in place of cos α, the constant A, for the rectifier.

Supply Circuits of Nonlinear Frequency-Reactance Characteristics

The theoretical method, including the formulas and curves, has been derived on the assumption that the supply-circuit reactances vary linearly with frequency. The question naturally arises as to how this method should be modified in order to apply it to circuits whose reactances at harmonic frequencies do not conform to this assumption. An empirical modification of the theoretical method of doing

Table II. Harmonic Currents for Grid-Controlled Rectifier

3,125 Kw, 625 Volts, 5,000 Amperes; A-C Supply, 12,000 Volts, Three-Phase

	A-C Harmonic Current in Amperes								
	I_{dc} = 1,000 Amperes A = 0.96 α = 16.5° IX/E_0 = 0.0106		I_{dc} = 2,500 Amperes A = 0.96 α = 16.5° IX/E_0 = 0.0266		I_{dc} = 4,000 Amperes A = 0.96 α = 16.5° IX/E_0 = 0.0425		I_{dc} = 4,000 Amperes A = 1 α = 0° IX/E_0 = 0.0425		
Frequency	Test	Theoret.	Test	Theoret.	Test	Theoret.	Test	Theoret.	Empirical
300	4.5	5.94	13.7	14.8	23	23.4	20.8	22.3	16.6
420	2.7	4.24	9.0	10.4	15.2	16.4	14.2	14.6	10.7
660	2.4	2.68	6.3	6.42	9.8	9.85	7.8	7.4	5.46
780	1.7	2.26	5.2	5.34	8.2	7.95	5.3	5.65	4.15
1,020	1.4	1.70	3.35	3.91	4.6	5.50	2.6	3.05	2.57
1,140	1.0	1.51	3.15	3.40	4.6	4.52	1.9	2.12	2.14
1,380	1.0	1.25	2.55	2.75	3.4	3.37	1.05	1.23	1.50
1,500	.9	1.14	2.30	2.42	3.0	2.77	.95	1.09	1.29
1,740	.8	.97	1.90	1.90	2.1	1.96	.95	.88	.97
1,860	.4	.88	1.42	1.73	1.85	1.66	.78	.77	.85
Root-mean-square	40		100		160		142		

Table III. Harmonic Currents for Grid-Controlled Rectifier

750 Kw, 600 Volts, 1,250 Amperes; A-C Supply, 2,300 Volts, Three-Phase

	I_{dc} = 1,250 Amperes A = 1.0 α = 0° IX/E_0 = 0.070		I_{dc} = 1,250 Amperes A = 0.945 α = 19° IX/E_0 = 0.070		I_{dc} = 1,250 Amperes A = 0.85 α = 31.7° IX/E_0 = 0.070		I_{dc} = 1,250 Amperes A = 0.75 α = 40.3° IX/E_0 = 0.070	
Frequency	Test	Theoret.	Test	Theoret.	Test	Theoret.	Test	Theoret.
300	39.4	37.4	45.3	40.5	52.7	41.6	58.6	41.7
420	23.6	24.5	22.1	27.7	23.2	28.9	22.1	29.3
660	12.1	10.1	15.7	15.9	18.8	17.3	18.2	17.8
780	7.35	7.17	10.8	12.1	10.8	14.0	11.0	14.5
1,020	3.74	3.46	9.74	7.65	11.5	10.0	12.6	10.4
1,140	2.06	2.66	5.41	6.02	4.25	8.31	5.27	9.0
1,380	2.33	1.84	3.07	3.86	7.25	5.87	8.16	6.80
1,500	1.89	1.74	2.58	2.30	2.98	5.10	3.38	5.77
1,740	1.43	1.33	2.57	1.45	4.34	3.48	5.36	4.52

	I_{dc} = 625 Amperes A = 1.0 α = 0° IX/E_0 = 0.035		I_{dc} = 625 Amperes A = 0.945 α = 19° IX/E_0 = 0.035		I_{dc} = 625 Amperes A = 0.89 α = 27.1° IX/E_0 = 0.035		I_{dc} = 1,875 Amperes A = 0.945 α = 19° IX/E_0 = 0.1045	
Frequency	Test	Theoret.	Test	Theoret.	Test	Theoret.	Test	Theoret.
300	18.1	19.8	23.1	20.8	23.1	21.0	65.9	58.8
420	10.8	12.0	9.0	14.6	9.90	14.8	33.8	39.0
660	7.38	7.11	8.45	9.02	8.84	9.25	19.4	19.8
780	5.40	5.45	5.18	7.33	5.67	7.66	12.3	14.35
1,020	3.42	3.11	6.39	5.36	6.07	5.72	7.47	6.60
1,140	2.33	2.30	2.95	4.45	2.94	4.90	2.46	4.02
1,380	1.54	1.21	4.91	3.60	4.42	3.88	1.78	1.58
1,500	1.06	1.02	2.11	3.10	2.58	3.44	1.09	1.10
1,740	1.03	.83	3.54	2.48	3.31	2.81	1.54	1.48

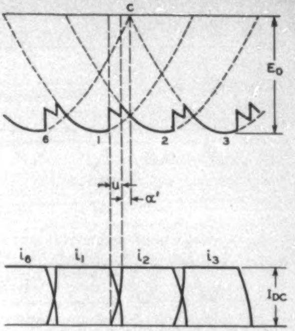


Figure 16. Voltage and current wave shapes of a six-phase star inverter under load

this for the case of a rectifier without control grids was proposed by Brown and Smith in the closing discussion of the paper[5] previously referred to. An extension of this method may be applied to the general case of a grid-controlled rectifier. In the modified theoretical method presented in this paper, the harmonic currents are estimated by the aid of figures 4 to 13 inclusive, using a fictitious reactance for the determination of the ratio IX/E_0. This fictitious reactance for each harmonic frequency is equal to the actual reactance at that frequency divided by the order of the harmonic. The value of the suggested modification of the theoretical method is yet to be determined, although by its use somewhat better checks are obtained for cases like that of table III. In that case, as mentioned previously, the supply-system reactance had nonlinear frequency-reactance characteristics.

Voltage and Current Wave Shapes in Supply Circuits With and Without A-C Filtering Equipment

When a-c filtering equipment is added to the supply circuit of a rectifier, this constitutes a special case of a supply circuit with nonlinear frequency-reactance characteristics. Some test results[9] are available from an installation including a-c filtering equipment consisting of seven three-phase resonant shunts tuned for the principal harmonic frequencies present. These resonant shunts are installed at the rectifier location and connected on the supply side of the rectifier transformer. For this installation the values of the harmonic currents supplied to the resonant shunts and the harmonic currents in the supply circuit are listed in table IV. In this table the second column gives the test values of harmonic currents supplied to the filtering equipment. Columns 3 and 4 give the corresponding harmonic currents calculated by the empirical method, and the modified theoretical method discussed in the preceding paragraph. Column 5 gives the theoretical values of harmonic currents in the supply lines for the condition without a filter. It will be noted that reasonable checks are obtained by both the modified theoretical and empirical methods. While in this particular case the empirical method gives somewhat better results, the modified theoretical method may find a wider field of application including that of the grid-controlled rectifier, although as pointed out previously only limited experience has been obtained using this method.

The a-c filtering equipment for the installation mentioned in connection with table IV was the first device to be built using tuned shunt elements for power rectifier application. This device accomplished a striking improvement in wave shape as may readily be seen by reference to figure 17. In this figure the primary current and voltage wave shapes from oscillograms are shown both without

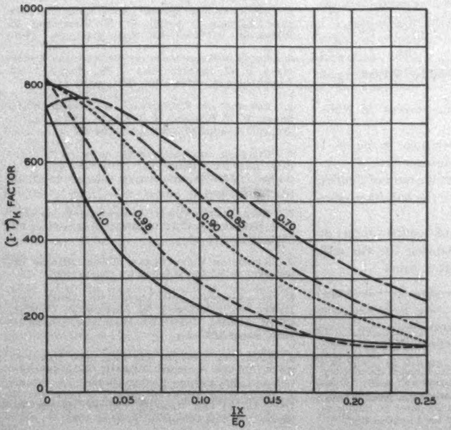
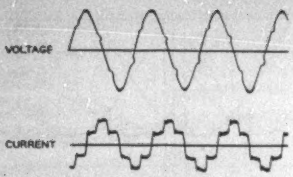
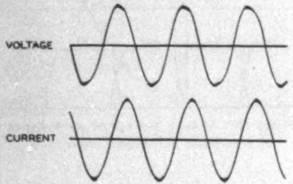


Figure 15. $(I \cdot T)_K$ factor for a 12-phase rectifier plotted as a function of IX/E_0 for several ratios of grid control



A-C RESONANT SHUNTS DISCONNECTED



A-C RESONANT SHUNTS CONNECTED

Figure 17. The a-c line current and voltage wave shapes of a six-phase rectifier without and with an a-c filter

Table IV. Harmonic Currents in the 4,600-Volt Supply Circuit of a Six-Phase 1,500-Kw Rectifier with A-C Filtering Equipment

	A-C Harmonic Current in Amperes I_{p1} = 120 Amperes; I_{dc} = 1,440 Amperes; A = 1.0					
	Amperes in Resonant Shunts			Amperes in Supply Lines		
Frequency	Test	Empirical	Modified* Theoret.	Theoret.** Shunts Off	Tests Shunts Off	Tests Shunts On
300	18.5	20.5	23.3	21.1	15.7	0.50
420	11.0	13.0	15.0	13.4	7.6	0.70
660	7.3	7.0	8.9	5.4	5.2	0.49
780	6.0	5.7	6.9	3.6	3.3	0.23
1,020	3.4	3.8	3.9	1.7	1.7	0.19
1,140	2.5	3.1	3.2	1.4	1.4	0.09
1,380	1.75	2.2	1.95	1.0	1.4	0.13
$I \cdot T$					38,000	3,600

* From 300 to 1,380 cycles equivalent reactance corresponds to that of transformer alone. Based on $IX/E_0 = 0.0275$ for these harmonic frequencies.

** Based on ratio of $IX/E_0 = 0.083$ for all frequencies.

and with the a-c filtering equipment connected in the circuit. The effectiveness of the filter in improving the wave shape may also be seen from a comparison of the last two columns of table IV which show an over-all reduction in harmonics of more than ten to one.

Conclusions

The harmonic distortion of voltage and current in the supply circuits of grid-controlled rectifiers varies considerably with the load and the grid-control ratio. Certain harmonics may be increased to as much as four times the values without grid control.

A theoretical method is presented for the determination of the harmonic currents and voltages in the supply circuits of grid-controlled rectifiers and inverters. General curves are given for the quick determination of the harmonic currents and $I \cdot T$ products for the range of conditions usually encountered in actual operation.

This method has been shown to give values which provide a very satisfactory comparison with actual test results.

Notation

E_{dc} = average d-c circuit voltage

I_{dc} = total direct current load, assumed constant

I = direct current per secondary phase group

E' = root-mean-square value transformer primary voltage, line-to-neutral

E = root-mean-square value of transformer secondary voltage, anode-to-neutral

E_0 = crest value of transformer secondary voltage, anode-to-neutral $= \sqrt{2}E$

R = E'/E = transformer ratio, supply side to rectifier side, line-to-neutral voltages

p = number of phases in each secondary phase group*

q = total number of rectifier phases

X = commutating reactance, one half of anode-to-anode reactance

L = X/ω henries commutating inductance

ω = $2\pi f$ angular velocity of supply

θ = angular velocity, radians in formulas $= \omega t$

u = angle of overlap, radians in formulas

α = angle of grid delay for rectifiers, radians in formulas

α' = angle corresponding to the time available for deionizing for inverters, radians in formulas

$u + \alpha'$ = angle of grid advance for inverters, radians in formulas

A = $\cos \alpha$ = grid-control ratio, ratio of d-c circuit voltage with grid control to value without grid control

i = instantaneous current in reference anode

m = order of harmonic $= nq \pm 1$ where n = integer 1, 2, 3, ...

a_m = coefficient of sine term of Fourier expansion for the mth harmonic, crest value

b_m = coefficient of cosine term of Fourier expansion for the mth harmonic, crest value

a_1 = coefficient of sine term of Fourier expansion for the fundamental, crest value

b_1 = coefficient of cosine term of Fourier expansion for the fundamental, crest value

I_m = $\frac{I}{\sqrt{2}}\sqrt{a_m^2 + b_m^2}$ = root-mean-square value of the mth harmonic of the Fourier expansion

I_1 = $\frac{I}{\sqrt{2}}\sqrt{a_1^2 + b_1^2}$ = root-mean-square value of the fundamental of the Fourier expansion

I_{pm} = primary line current for the mth harmonic, root-mean-square value

I_{p1} = primary line current for the fundamental, root-mean-square value

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* p may also be defined as

$$\frac{360 \text{ degrees}}{(\text{conducting period in degrees}) - (\text{angle of overlap in degrees})}$$

The values of p for some of the common connections are: $p = 3$ for 6-phase double-wye and 12-phase quadruple-wye with interphase transformers; $p = 6$ for 6-phase star and 12-phase in double 6-phase relation; and $p = 12$ for 12-phase star.

Discussion

F. O. Stebbins (nonmember; General Electric Company, Schenectady, N. Y.): The paper by Messrs. Evans and Muller gives one more step in developing methods for estimating the wave shapes of mercury-arc rectifiers. The authors point out that the problem is divided into four different types of calculations. The first three parts consist of the wave shapes on the d-c side of a rectifier without grids, the wave shapes on the a-c side of a rectifier without grids, and the wave shapes on the d-c side of a rectifier equipped with grids. The authors now have covered the final phase of this problem, namely the wave shapes on the a-c side of a rectifier equipped with grids.

Subsequent to publication by the writer of the paper on the wave shapes on the d-c side of a rectifier equipped with grids, reference 3 in the authors' paper, work was continued and formulas similar to those given in this paper were derived for the wave shapes of the current on the a-c side. The results obtained with these formulas circuit may have several resonance points the agreement obtained between theoretical and test values was not as close, but was acceptable for practical purposes.

O. K. Marti (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The authors of this interesting paper have summarized in an instructive way the results of a very important investigation. In large installations it is very essential to predetermine the magnitude of the harmonic currents, especially if grid voltage control is used. The analytical solution to determine the individual harmonic currents is rather tedious, and therefore the curves given by the authors will be of great assistance in analyzing systems in the future.

About two years ago we were confronted by such a problem—a very involved one. This was especially complicated by the fact that a large rectifier capacity was concentrated in one station. I am referring to the 55,000-kw rectifier installation at the Alcoa plant of the Aluminum Company of America. This station has ten 5,500-kw converting units consisting each of one transformer with two 12-anode rectifier tanks. The systems feeding the rectifiers sometimes have to be connected with systems spreading over a wide territory, and therefore the exposures existing between the transmission system and the telephone lines were of necessity of considerable magnitude.

Preliminary investigations showed that it would be necessary to go to a multiphase system far more elaborate than hitherto attempted. It was therefore decided to tackle the problem by building up a miniature test set instead of approaching it mathematically as was done by the authors of the paper. The set consisted of five units, each unit having a model rectifier transformer with six grid-controlled tubes (each tube representing an anode) and other auxiliary equipment.

Our first preliminary study disclosed the fact that the use of shunt filters as described by the authors could not be considered the way for solving our problem, as the cost of such filters proved to be prohibitive. A system of 30 phases was therefore set up check the theoretical calculations given by the authors.

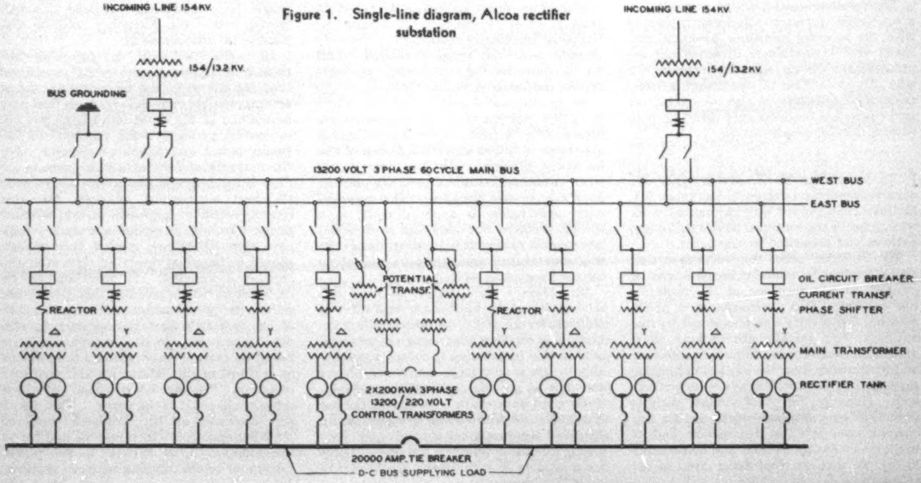

Figure 1. Single-line diagram, Alcoa rectifier substation

As a suggestion for practical applications the results presented in the authors' paper might be plotted in terms of per cent harmonic. The amount of harmonic current can then be determined directly from the curves for different rectifier loads and voltage control ratios.

In connection with the data given in table III of the paper it would be interesting to know if the test measurements were made in the factory or in the field. It has been our experience that in tests made in the factory where the impedance of the power-supply circuit approximates a straight line a good check between theoretical and measured values is obtained. However, in tests made in the field where the power-supply

Figure 2. Twenty grid-controlled mercury-arc rectifiers, each rated 2,750 kw, 600 volts, at Alcoa plant of Aluminum Company of America

using autotransformers as phase shifters in order to obtain the necessary displacement between the individual units. A thorough investigation was carried out in co-operation with the engineers of the Bell Telephone Laboratories, Inc., using this model set-up at our test laboratory.

Since very little power was required, the study of the wave shapes with oscillograph and wave-shape analyzer for this system and these load characteristics could be carried out very easily and with the greatest convenience. Some of the results obtained with this set will be shown and described in a paper under preparation by T. A. Taylor of the Bell Telephone Laboratories and the writer, and will deal in detail with this installation in regard to co-ordination of power and telephone systems.

The method of phase shifting by means of autotransformers was finally adopted for all three plants. A single-line diagram with all the main equipment, such as phase-shifters, reactors, rectifier transformers, and tanks, is shown in figure 1 of this discussion. Figure 2 shows the rectifier room with control cubicles, heat exchangers, high-speed d-c breakers, and rectifier tanks.

The results obtained with this model 30-phase system set-up checked very favorably with the actually measured harmonic currents, and its usefulness exceeded our expectations. We therefore felt that such a way of approaching this problem to determine the harmonics in the a-c circuits of grid-controlled rectifiers and inverters may deserve further consideration.

R. D. Evans and **H. N. Muller, Jr.:** We were very much interested to learn that Mr. Stebbins has carried out theoretical work which checks the formulas developed by the authors and presented in the paper.

Mr. Stebbins offers the suggestion that the individual harmonic currents might be plotted as a percentage of the total a-c line current. This alternative form of expressing the results was considered by the authors. For certain applications it is necessary to determine the a-c line current and when this is done the method of plotting suggested by Mr. Stebbins is quite convenient. However, for other studies, such as inductive co-ordination work, the a-c line current need not be determined and it becomes somewhat simpler and more direct to use the method of plotting given in the paper. The quantities which have been used for plotting the general curves are those which are always available for any particular rectifier installation and it seemed preferable to use only these quantities instead of an additional derived quantity, the a-c line current, even though this must frequently be calculated. Perhaps it should be pointed out that both methods of plotting the general curves have the characteristic which permits one to visualize the ratios to be expected as a percentage or per unit ratio and with a little experience a sense of the proper magnitude to be expected is readily obtained.

In response to Mr. Stebbins' request we would like to point out that the data given in table III of the paper were obtained from factory tests and also that the data for tables II and IV were obtained from field tests. The supply circuit used in connection with the factory tests had a harmonic impedance characteristic which did not vary linearly over the important range of frequencies. This fact caused some of the comparisons between calculated and test values to vary considerably, although the results are still acceptable for practical purposes. The supply circuit used in the field tests of table II was selected because its harmonic impedance characteristic did vary linearly over the range measured. This fact accounts for the exceptionally accurate checks encountered in this table.

We are interested to note that Mr. Marti is of the opinion that the general curves presented in the paper will be of considerable assistance in future analytical studies of the harmonic problem. His laboratory work with miniature rectifiers presents another approach to this problem. This arrangement was made to apply directly to a specific problem, but additional work would be required to permit presenting the results in a general form comparable to that given by the analytical solution.

Mr. Marti's discussion of the use of a scheme involving multiphase operation of rectifiers for Alcoa is of considerable interest. Because of the large number of anodes available in this installation it becomes practicable to use a very large number of phases and thus to provide an installation of relatively good wave shape. Of course, the use of 6-phase rectifiers which are electrically displaced from each other to give in effect a large number of phases is not new. There are a number of installations where two 6-phase units have been operated from delta and star transformers to give the equivalent of 12-phase operation. We are informed that in one European installation two 12-phase rectifiers were connected through phase-shifting transformers to give the equivalent of 24-phase operation. This arrangement was adopted for the purpose of eliminating objectionable 11th and 13th harmonic currents which were amplified by partial resonance in the supply system. The particular scheme described by Mr. Marti is of interest because of the size of the installation and the number of units involved. The installation which he has shown in figure 1 of his discussion would appear to be the equivalent of a 60-phase rectifier system when all the units are in service and carrying symmetrical loads.

Mr. Marti comments on the use of connections giving the equivalent of a large number of phases as preferable to the use of an a-c filter. The authors recognize that where this multiplicity of phases is available the solution mentioned presents a more economical arrangement than filters. However, in the more usual case the number of units and particularly the number of anodes would be considerably less and this fact would make the foregoing solution impossible or uneconomical.

In connection with the foregoing discussion it should of course be recognized that the use of an a-c filter is only one of several possible remedial measures that may be applied in the event of an inductive co-ordination problem being encountered between power and telephone circuits. For the majority of rectifier installations an a-c filter is not required and would not provide the best engineering solution. For this reason, rectifier equipment is sold without filters. In case co-ordination studies indicate that filters are needed their design should be based on results of tests after the rectifier is installed. It may however be desirable for the interested utilities to obtain during the co-ordination studies an estimate of the cost of a filter for comparison with other measures. Such an estimate may be based on certain recommended proportions as outlined in the Edison Electric Institute report on "Rectifier Wave Shape" to which reference is given in the paper. This report also discusses all the available types of remedial measures which may be applied to the communication system, to the power system, or to the coupling between systems.

Equivalent Circuit Impedance of Regulating Transformers

J. E. CLEM
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As SYSTEMS grow in complexity and service standards grow higher, the need for more accurate determination of system characteristics increases. From time to time the question of how to handle the impedance introduced into the circuit by a regulating transformer has arisen. This paper has been written to present general equations by means of which the equivalent circuit impedance of regulating transformers may readily be determined.

Regulating transformers are in effect autotransformers, but differ from them in that the series winding is on a separate core and receives its excitation from a section of the shunt winding. This difference introduces considerable complexity into the determination of the impedance introduced into the circuit.

1. Input to Shunt Winding—Output From Series Winding

Refer to figure 1 for the determination of the impedance from the shunt winding to the shunt plus series winding. The output voltage E_y is the input voltage E_x plus for step up or boost, or minus for step down or buck, the voltage E_a introduced into the circuit by the series transformer. As an equation

$$E_y = E_x \pm E_a \tag{1}$$

But the voltage E_a is the voltage induced in the series transformer less the impedance drop:

$$E_a = kE_s \mp IZ_a \tag{2}$$

and the voltage E_s is equal to the voltage induced in the excitation section less the impedance drop

$$E_s = m(E_x \mp mkIZ_{ps}) \tag{3}$$

Now substitute (3) into (2) and (2) into (1) and get

$$E_y = (1 \pm mk)E_x - (m^2k^2Z_{ps} + Z_a)I \tag{4}$$

from which

$$(1 \pm mk)E_x - E_y = (m^2k^2Z_{ps} + Z_a)I \tag{5}$$

The left-hand term of (5) is the voltage drop E from the primary to the secondary circuit reckoned at the external terminal of the series transformer, so that

$$E = (m^2k^2Z_{ps} + Z_a)I \tag{6}$$

To express this on a per-unit basis, both sides of (6) should be divided by the no-load ratio-voltage at the external terminal of the series transformer reckoned from the voltage of the shunt coil, that is by $(1 \mp mk)E_p$. And then

$$\mathbf{Z}_{xy} = \frac{(m^2k^2Z_{ps} + Z_a)I}{(1 \pm mk)E_p} \tag{7}$$

The plus sign is to be used for step up and the minus sign for step down.

2. Input to Series Winding—Output From Shunt Winding

Refer to figure 2 for the determination of the impedance from the shunt plus series winding to the shunt winding The output voltage E_y is the input voltage E_x minus, for step down or buck, or plus, for step up or boost, the voltage E_a introduced into the circuit by the series transformer

$$E_y = E_x \mp E_a \tag{8}$$

Since the power flow is into the series coil and out from the shunt coil, the relationship between E_a and E_s is now

$$E_a = kE_s \pm IZ_a \tag{9}$$

For the same reason the relationship between E_y and E_s becomes

$$E_s = m(E_y \pm mkIZ_{ps}) \tag{10}$$

When (10) is substituted into (9) and (9) in turn substituted into (8) there results

$$E_y = E_x \mp mkE_y - (m^2k^2Z_{ps} + Z_a)I \tag{11}$$

from which

$$E_x - (1 \pm mk)E_y = (m^2k^2Z_{ps} + Z_a)I \tag{12}$$

The left-hand term of (15) is the voltage drop E from the primary to the secondary circuit, reckoned at the external terminal of the series transformer, so that

$$E = (m^2k^2Z_{ps} + Z_a)I \tag{13}$$

To express this on a per-unit basis, both sides of (13) should be divided by the no-load ratio-voltage at the external terminal of the series transformers, reckoned from the voltage of the shunt coil. Then

$$\mathbf{Z}_{xy} = \frac{(m^2k^2Z_{ps} + Z_a)I}{(1 \pm mk)E_p} \tag{14}$$

The plus sign is to be used for step down and the minus for step up.

Equation 14 is identical with 7 indicating that direction of power flow has no effect. This should have been expected but circumstances indicated that it was desirable to demonstrate it.

3. Equivalent Primary to Secondary Impedance by Short-Circuit Test

Equations 7 and 14 can be obtained in a slightly different manner. In (4) let E_y be zero, that is, corresponding to an impedance test with the output side short-circuited. Then E_x becomes the impedance voltage E corresponding to the condition of current I in the series coil, so that (4) becomes

$$(1 \pm mk)E = (m^2k^2Z_{ps} + Z_a)I \tag{15}$$

$$E = \frac{(m^2k^2Z_{ps} + Z_a)\,I}{1 \pm mk} \tag{16}$$

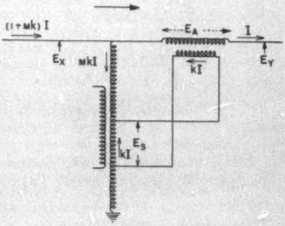

Figure 1

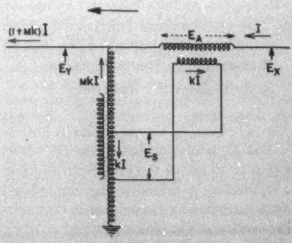

Figure 2

Paper number 39-100, recommended by the AIEE committee on electrical machinery, and presented at the AIEE North Eastern District meeting, Springfield, Mass., May 3-5, 1939. Manuscript submitted March 24, 1938; made available for preprinting March 28, 1939.

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and on a per-unit basis

$$\mathbf{Z}_{xy} = \frac{E}{E_p} = \frac{(m^2k^2Z_{ps} + Z_a)}{(1 \pm mk)} \cdot \frac{I}{E_p} \qquad (17)$$

Reference to (7) shows that (17) is identical with it.

Now in (11) let E_y be zero, that is, corresponding to an impedance test with the output side short-circuited. Then E_x becomes the impedance voltage E corresponding to the condition of current I in the series coil, so that (11) becomes

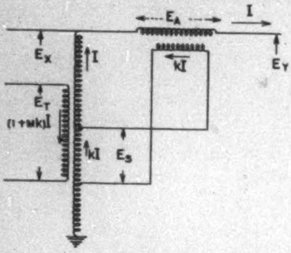

Figure 3

$$E = (m^2k^2Z_{ps} + Z_a)I \qquad (18)$$

Since the measurement is made on the series transformer side the no-load voltage is $(1 \pm mk)E_p$. To convert into a per-unit value both sides must be divided by $(1 \pm mk)E_p$.

$$\mathbf{Z}_{xy} = \frac{E}{(1 \pm mk)E_p} = \frac{(m^2k^2Z_{ps} + Z_a)I}{(1 \pm mk)E_p} \qquad (19)$$

Reference to (14) shows that (19) is identical with it.

4. IMPEDANCE FROM TERTIARY WINDING TO SHUNT WINDING OF SHUNT TRANSFORMERS

This is simply

$$\mathbf{Z}_{tx} = Z_{tp}(1 \pm mk)\frac{I}{E_p} \qquad (20)$$

5. IMPEDANCE FROM TERTIARY WINDING OF SHUNT TRANSFORMER TO SHUNT WINDING PLUS SERIES WINDING

Refer to figure 3. As before

$$E_y = E_x \pm E_a \qquad (21)$$

But E_x is now derived from E_t. It is equal to E_t minus the drop from winding t to winding p, minus or plus the mutual drop produced by the current in the exciting section of the shunt winding.

$$E_x = E_t - IZ_{tp} \mp mkIM_{ps} \qquad (22)$$

In which

$$M_{ps} = (Z_{tp} - Z_{ps} + Z_{st})/2 \qquad (23)$$

And in the same manner

$$E_a = kE_s \mp IZ_a \qquad (24)$$

and

$$E_s = m(E_t \mp mkIZ_{ts} - IM_{ps}) \qquad (25)$$

The upper sign corresponds to the condition when the voltage at the external terminal of the series transformer is greater than the voltage across the shunt transformers, the bottom sign when it is less.

Now substitute (25) into (24) and then both (24) and (22) into (21) and

$$E_y = (1 \pm mk)E_t - I(Z_{tp} + m^2k^2Z_{ts} + 2mkM_{sp} + Z_a) \qquad (26)$$

and then

$$(1 + mk)E_t - E_y = (Z_{tp} + m^2k^2Z_{ts} + 2mkM_{sp} + Z_a)I \qquad (27)$$

As before the left-hand term of this equation is the impedance drop E as it appears at the external terminal of the series transformer where the no-load ratio-voltage is $(1 \pm mk)E_p$. And so

$$E = (Z_{tp} + m^2k^2M_{sp} + 2mkM_{sp} + Z_a)I \qquad (28)$$

and on a per-unit basis

$$\mathbf{Z}_{ty} = \frac{E}{(1 \pm mk)E_p} \qquad (29)$$

$$\mathbf{Z}_{ty} = \frac{Z_{tp} + m^2k^2Z_{ts} \pm 2mkM_{ps} + Z_a}{1 \pm mk}\,\frac{I}{E_p} \qquad (30)$$

6. SUMMARY OF EQUATIONS—BOOST CONDITION

$$\mathbf{Z}_{xy} = \frac{r^2Z_{ps} + Z_a}{1 + r}\,\frac{I}{E_p} \qquad (31)$$

$$\mathbf{Z}_{yt} = \left(Z_{tp} + rZ_{st} + \frac{rZ_{ps} + Z_a}{1 + r}\right)\frac{I}{E_p} \qquad (32)$$

$$\mathbf{Z}_{tx} = Z_{tp}(1 + r)\frac{I}{E_p} \qquad (33)$$

The relationship

$$M_{ps} = Z_t = (Z_{tp} - Z_{ps} + Z_{st})/2 \qquad (23)$$

has been inserted in (30) to get (32). Also r has been written for mk.

7. SUMMARY OF EQUATIONS—BUCK POSITION

$$\mathbf{Z}_{xy} = \frac{r^2Z_{ps} + Z_a}{1 - r} \cdot \frac{I}{E_p} \qquad (34)$$

$$\mathbf{Z}_{yt} = \left(Z_{tp} - rZ_{st} + \frac{rZ_{ps} + Z_a}{1 - r}\right)\frac{I}{E_p} \qquad (35)$$

$$\mathbf{Z}_{tx} = Z_{tp}(1 - r)\frac{I}{E_p} \qquad (36)$$

The impedances of the various branches can be determined by the conventional three-winding theory, when care is taken to see that the equations are properly handled. Equations 31 and 34 give the positive- and negative-sequence impedances and 31, 32, 33 or 34, 35 and 36 as a network give the zero-sequence impedances.

Effect of Angular Component

The foregoing development applies to a regulating transformer for in-phase, or direct, regulation only. The same method of analysis may be applied to a regulating transformer that has both direct and angular regulation. Only the final equations will be given. Refer to figure 4—phase sequence is ABC.

$$\mathbf{Z}_{ps} = \mathbf{Z}_1 + \mathbf{Z}_2 + \mathbf{Z}_3 \qquad (37)$$

$$\mathbf{Z}_1 = m_1k_1\left(m_1k_1Z_{p1} - am_2k_2M_{12} + a^2m_3k_3M_{31} + \frac{Z_{a1}}{m_1k_1}\right)\frac{I}{E_s} \qquad (38)$$

$$\mathbf{Z}_2 = m_2k_2\left(m_2k_2Z_{p2} - am_3k_3M_{23} - a^2m_1k_1M_{12} + \frac{Z_{a2}}{m_2k_2}\right)\frac{I}{E_s} \qquad (39)$$

$$\mathbf{Z}_3 = m_3k_3\left(m_3k_3Z_{p3} + am_1k_1M_{31} - a^2m_2k_2M_{23} + \frac{Z_{a3}}{m_3k_3}\right)\frac{I}{E_s} \qquad (40)$$

$$E_s = (1 \pm m_1k_1 \mp a^2m_2k_2 \pm am_3k_3)\,E_p \quad \text{at no load} \qquad (41)$$

$$\mathbf{Z}_{st} = \mathbf{Z} + \mathbf{Z}_1 + \mathbf{Z}_2 + \mathbf{Z}_3 \qquad (42)$$

$$\mathbf{Z} = (Z_{pt} \pm m_1k_1M_{p1} \mp m_2k_2M_{p2} \pm m_3k_3M_{p3})\frac{I}{E_s} \qquad (43)$$

$$\mathbf{Z}_1 = m_1k_1\left(m_1k_1Z_{t1} \pm M_{p1} - m_2k_2M_{12} + m_3k_3M_{31} + \frac{Z_{a1}}{m_1k_1}\right)\frac{I}{E_s} \qquad (44)$$

$$\mathbf{Z}_2 = m_2k_2\left(m_2k_2Z_{t2} \mp M_{p2} - m_3k_3M_{23} - m_1k_1M_{12} + \frac{Z_{a2}}{m_2k_2}\right)\frac{I}{E_s} \qquad (45)$$

$$\mathbf{Z}_3 = m_3k_3\left(m_3k_3Z_{t3} \pm M_{p3} + m_1k_1M_{31} - m_2k_2M_{23} + \frac{Z_{a3}}{m_3k_3}\right)\frac{I}{E_s} \qquad (46)$$

$$\mathbf{Z}_{tp} = Z_{tp}\frac{I_p}{E_p} \qquad (47)$$

Equation 47 should be handled carefully. The (+) applies when the boosters increase the voltage or increase the phase angle, that is, for boost in voltage or boost in phase angle.

Note that the quantities $\mathbf{Z}_1$, $\mathbf{Z}_2$, and $\mathbf{Z}_3$ in (42) are not the same as in (37).

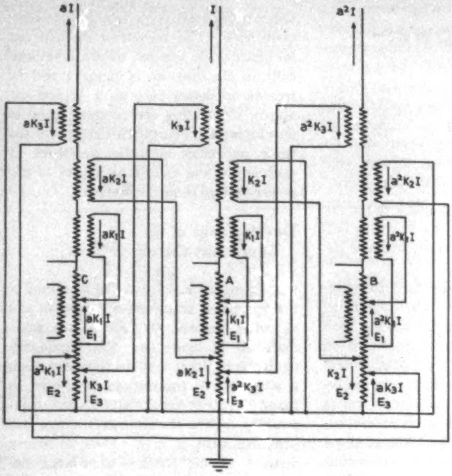

Figure 4

$\mathbf{Z}_{ps}$ = per-unit impedance from circuit which excites shunt winding, to circuit supplied from booster winding. See figure 4

$\mathbf{Z}_{st}$ = per-unit impedance from circuit supplied from booster winding, to tertiary winding on shunt transformer

$\mathbf{Z}_{tp}$ = per-unit impedance from tertiary winding on shunt transformer, to circuit which excites shunt winding

Subscripts 1, 2, 3, respectively refer to in-phase boosters, a^2 phase boosters, and a phase boosters, respectively; see figure 4.

Subscripts p, t, refer to total shunt windings and tertiary windings on shunt transformers.

k = ratio of turns in booster transformers, series line coil to excited coil

m = ratio of turns in exciting sections of shunt winding to total turns in shunt winding

All impedances of windings in the shunt transformers are in ohms, and on the basis of the total turns in the shunt windings.

Impedances of the booster transformer are in ohms, and on the basis of the turns in the series line coil.

Mutual impedances in (37), (38), (39), are referred to in the shunt winding p.

Mutual impedances in (43), (44), (45), (46), are referred to the tertiary winding t.

For example, M_{12} in (38) and (39) is given by

$$M_{12} = \frac{Z_{p1} - Z_{12} + Z_{2p}}{2} \qquad (48)$$

M_{12} in (44) and (45) is given by

$$M_{12} = \frac{Z_{t1} - Z_{12} + Z_{2t}}{2} \qquad (49)$$

Any two of the booster coils may be combined. Frequently the two angle boosters are combined to obtain a quadrature component. In this case k_q would be used to designate the turn ratio of the quadrature booster transformers and would replace both k_2 and k_3 in the equations, no other change being needed.

The impedance given by equation 37 is for positive sequence. For negative sequence interchange the operators a and a^2. For zero-sequence place the operators a and a^2 in (37), (38), and (39), equal to 1 to get the through impedance circuit to circuit, and use in the conventional three-circuit network with the other two zero-sequence impedances, circuit to ground, to get the proper branch impedances.

When the transformer neutral is grounded through an impedance of Z_n ohms, the impedances of the branches of the zero-sequence network are affected. They become, with the subscript g added to indicate the impedance when grounded through a neutral grounding impedance,

$$\mathbf{Z}_{gps} = \mathbf{Z}_{ps} + 3(m_1k_1 - m_2k_2 + m_3k_3)^2\mathbf{Z}_n \qquad (50)$$

$$\mathbf{Z}_{gst} = \mathbf{Z}_{st} + 3\mathbf{Z}_n \qquad (51)$$

$$\mathbf{Z}_{gtp} = \mathbf{Z}_{tp} + 3\mathbf{Z}_n \qquad (52)$$

$$\mathbf{Z}_n = Z_n\frac{I}{E_s} \qquad (53)$$

List of Symbols

E_x = primary, or input, voltage
E_y = secondary, or output, voltage
E_a = voltage introduced into the circuit by the series transformer
E_p = voltage across total winding of shunt transformer
E_s = voltage across exciting section of shunt transformer
E_t = voltage across tertiary winding of shunt transformer
k = ratio of turns, series winding to excited winding, of series transformer
m = ratio of turns, excitation section to total turns, of shunt transformer
r = mk
Z_a = impedance of series transformer, in ohms based on turns in series winding
Z_{ps} = impedance of shunt transformer from total winding to excitation section, in ohms based on total turns of shunt winding
Z_{st} = impedance of shunt transformer from excitation section to tertiary winding, in ohms based on total turns of shunt winding
Z_{tp} = impedance of shunt transformer from tertiary winding to total shunt winding in ohms based on total turns of shunt winding
$\mathbf{Z}_{xy}$ = per-unit impedance from input to output side
$\mathbf{Z}_a$, $\mathbf{Z}_{ps}$, $\mathbf{Z}_{st}$, $\mathbf{Z}_{tp}$ = per-unit impedances based on the total turns of the shunt coil, except $\mathbf{Z}_a$ which is based on the turns in the series line coil. Based on current and voltage of circuit connected to external terminal of series coil

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Discussion

W. A. Lewis (Cornell University, Ithaca, N. Y.): The paper by Mr. Clem covers a similar subject to the paper by Doctor Hobson and myself ("Regulating Transformers in Power System Analysis, AIEE Transactions, volume 58, 1939, pages 874–86), and a comparison of the two may serve to bring out a little more strongly the principles involved. Mr. Clem develops the equivalent circuits for one general type of regulating transformer, in which the exciting windings are star-connected. His method is basically the same as ours, and his equations could be applied directly to the figures in our paper.

If the exciting transformers are connected in delta, a 30-degree phase shift is introduced in the voltage added to the incoming voltage by the series winding, and a transformer which originally had a star-connected exciting winding becomes a phase-angle regulator, and the transformer which was originally designed for phase-angle regulation can be arranged for voltage regulation when the exciting windings are connected in delta. The unusual phenomena described in our paper are characteristic primarily of regulating transformers using the delta connection for the exciting circuit, and therefore do not appear when only the star-connected case is considered.

In Mr. Clem's paper the final results are given in per-unit or per-cent notation, but the basic data on the transformer elements are introduced in ohms. In our paper, on

Regulating Transformers in Power-System Analysis

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IN THE analysis of power systems it is customary to represent generators, transformers, and transmission lines by their equivalent circuits. The resulting circuit network is solved either by representation on a network calculator, from which the solution is read directly, or analytically by successive simplification of the network. When the network has been simplified as far as possible, it is usually relatively easy to solve the simplified network, by the application of Kirchhoff's laws, for the currents in the remaining circuits and the voltages at the remaining terminals. When this solution has been obtained, the steps of simplification are reversed until the original network is restored, the currents and voltages being calculated at each step, until the desired quantities are finally obtained for the original network. When the system is unbalanced, as by an unbalanced fault condition, the method of symmetrical components[1] is widely used. Equivalent networks are derived for the positive-, negative-, and zero-sequence components of current and voltage. Interconnections between the sequence networks are made, corresponding to the unbalanced condition, and the resulting network is solved by the methods just described.

The equivalent circuits used to represent complicated power and regulating transformers have not previously been published and they often constitute an important element of the power-system representation. Furthermore, the analysis of systems involving such transformers has brought to the attention of the authors several unusual problems, whose solution is not well known. Believing the solution of these problems would be of general interest, the authors have presented several examples in this paper, which are illustrative of the problems encountered.

The regulating transformer may introduce a phase shift in the voltage and current as well as a change in magnitude. This differs from the usual star-delta power transformation in that the angle of phase shift is not fixed but depends on the tap position. Also, it quite frequently happens that there are connections between the two circuits (connected by the regulating transformer)other than through the regulating transformer itself. The other connection (or connections) may be direct, as is usually the case when the regulator is used to control the flow of power in a closed loop, or may be through another transformer having transformation characteristics differing from those of the regulator with which it is essentially connected in parallel. A number of the winding connections used in regulating transformers result in a transformation ratio for zero-sequence current and voltage which is unequal to the transformation ratio for positive- or negative-sequence quantities. The regulating transformer for phase-angle control, shown schematically in the diagram of figure 1 will be treated in detail here as a typical example, illustrating the methods used in developing the equivalent circuits for the three sequences and the treatment of each equivalent circuit as a part of the power-system sequence network.

Development of the Equivalent Circuit

Two magnetically coupled windings of a single-phase transformer having n_1 and n_2 turns, respectively, are shown schematically in figure 2*a*. The customary equivalent circuit used to represent such a single-phase transformer is shown in figure 2*b*, in which Z_A and Z_B are components of the transformer leakage impedance, with a more-or-less arbitrary division of the leakage impedance between Z_A and Z_B. Z_M is the so-called "magnetizing shunt branch." Since the numerical value of Z_M is very large compared to Z_A and Z_B, for most calculations, figure 2*b* is approximated by figure 2*c*, where Z_M is considered infinite. Either of these circuits has serious deficiencies as a device representing the actual transformer; the voltage and current transformation effected by transformer action is not represented in the equivalent circuit, and the circuit terminals a and a' are not insulated from each other as in the actual transformer. These disadvantages are evidenced particularly when analyzing transformer circuits wherein several windings or phases are interconnected. To overcome these deficiencies the authors have found it expedient to use the equivalent circuit shown in figure 2*d*, which combines the circuit of figure 2*b* with an ideal transformer. The ideal transformer is defined as having infinite

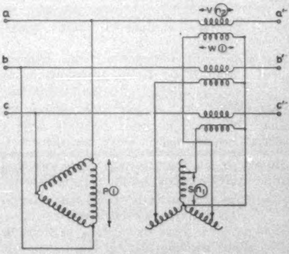

Figure 1. Typical phase-angle regulating transformer

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The authors wish to acknowledge the assistance of their associates, particularly Clayton F. Hall, whose aid in checking the derivations and the illustrations has been invaluable.

[1] For numbered reference, see end of paper.

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the other hand, when our results are expressed in per cent, the basic data on the transformer elements are also expressed in per cent, on the kilovolt-ampere parts which that particular element will be required to carry when the regulating transformer as a whole is carrying rated kilovolt-amperes. When these differences are reconciled, our results are in agreement with the results given by Mr. Clem. We have felt that the form we have given would be somewhat more useful for preliminary estimating purposes, since the first step in the design of a regulating transformer is to determine the voltage and kilovolt-ampere rating of each transformer element. With this information at hand, it is usually possible to estimate from typical designs a per-cent reactance of each transformer element on its own kilovolt-amperes, and these values may be immediately introduced into the formulas to determine the over-all characteristics, on the kilovolt-amperes of the entire regulating transformer as a basis.

exciting impedance (zero exciting current or no load current) and zero leakage impedance, and serves to transform voltage and current without impedance drop or power loss; the ideal transformer thus restores actual voltage and current relationships at the terminals *a* and *a'*. The circuit of figure 2*e* is obtained from figure 2*d* by converting the impedance Z_B to the E_a' voltage base (by multiplying Z_B by the square of the voltage ratio). This process may be thought of as "sliding the ideal transformer through" the impedance Z_B. If the exciting, or no load, current may be neglected (Z_M considered as infinite) the circuit of figure 2*e* becomes figure 2*f*.

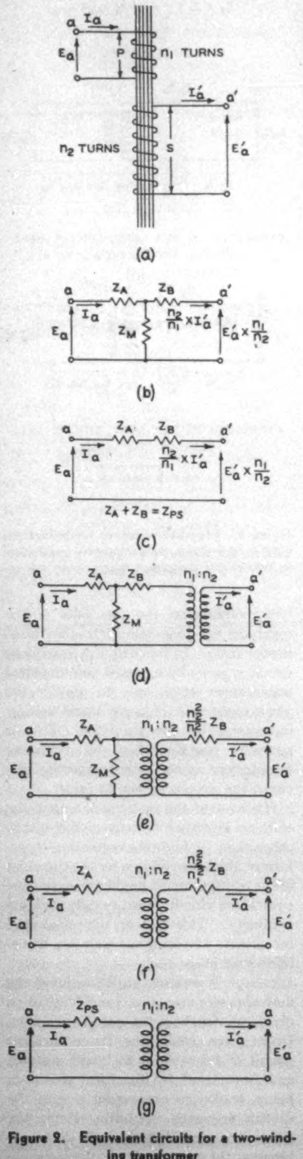


Figure 2. Equivalent circuits for a two-winding transformer

Finally, if Z_M is considered infinite, the circuit of figure 2*d* becomes figure 2*g*, in which the two parts of the leakage impedance, Z_A and Z_B, combine into the complete leakage impedance Z_{PS}, where

$$Z_{PS} = Z_A + Z_B$$

In most developments the circuit of figure 2*g* will be found most convenient, although in some cases it becomes desirable to have part of the leakage impedance associated with each winding, and the circuit of figure 2*f* may be used.

To be perfectly definite, Z_{PS} is understood to mean the leakage impedance, as measured in ohms, with the *S* winding short-circuited, and voltage applied to the *P* winding. When the test is reversed, with voltage applied to the *S* winding, and the *P* winding short-circuited, the impedance is denoted by Z_{SP}. It is obvious from the development given that, when Z_M may be considered infinite,

$$Z_{SP} = \frac{n_2^2}{n_1^2} Z_{PS}$$

Phase-Angle Regulator

The diagram of figure 1 is redrawn in figure 3, using the type of equivalent circuit shown in figure 2*g* for each of the single-phase units involved. It will be noted that each exciting transformer is denoted by the letters *PS*, *P* representing the primary winding and *S* the secondary. Also, each series transformer is denoted by *VW*, *V* denoting the winding in series with the line, and *W* the winding connected to the exciting transformer. The impedances Z_{PS} and Z_{VW} are the leakage impedances of the exciting and series transformers, respectively. For convenience, the relative numbers of turns of the transformer windings are taken as $1:n_1$, for the exciting transformer and $1:n_2$ for the series transformer, and each winding is assumed to have a number of turns proportional to the associated number or letter enclosed in a circle on the diagram. As the tap position of winding *S* changes, it must be noted that n_1 and also Z_{PS} change. Care must be taken to use the proper values for each tap.

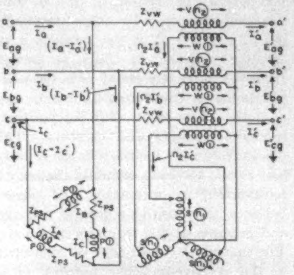


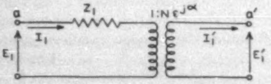
Figure 3. Three-phase equivalent circuit for the transformer of figure 1

It is obvious that the circuit shown is symmetrical, that is, the construction of all three phases is the same. It is well known in the theory of symmetrical components, that in such cases, positive-sequence currents flowing produce only positive-sequence reactions, so that the equivalent circuit for the positive-sequence diagram may be derived by circulating positive-sequence currents through the regulating transformer and computing the voltage relations, using the diagram of figure 3. The details of this procedure are given in appendix I.

Equations 15 and 17 of appendix I give the transformer action of the regulator to positive-sequence votlages and currents, *N* being the transformation ratio and α being the angle of phase shift. Equation 18 gives the impedance of the regulating transformer; namely, $Z_1 = 1/N^2 \times (n_1^2 n_2^2 Z_{PS} + Z_{VW})$ ohms, on the voltage base of the left-hand, or input, circuit as viewed from the terminals *a*, *b*, and *c*. It should be noted that the transformation ratio, the angle of phase shift, and the impedances Z_{PS} and Z_1 are each functions of the tap setting (that is, functions of n_1), and vary with the tap being used. When the tap changer mechanism is in the neutral position $N = 1$, $\alpha = 0$, and $Z_1 = Z_{VW}$ ohms.

Any circuit satisfying equations 15, 17, and 18, will be a positive-sequence equivalent circuit for the regulating transformer. Those who are familiar with the use of symmetrical components know that a single-phase diagram may be used to represent the three phases if the phase quantities are balanced and symmetrical as, for example, under the positive-sequence conditions assumed in appendix I. The suggested positive-sequence equivalent circuit is given in figure 4*a* in which E_1 and I_1 are, respectively, the positive-sequence components of the line-to-ground voltages and line currents, at the input terminals *a*, *b*, and *c*; E_1' and I_1' are, respectively, the positive-sequence components of the line-to-ground voltages and currents at the output terminals *a'*, *b'*, and *c'*; Z_1 is the impedance to positive sequence, in ohms, as viewed from the input terminals; N is the positive-sequence transformation ratio; and α is the phase-angle shift for positive-sequence voltages and currents. The ideal transformer included in the equivalent circuit serves to maintain the proper relationship, in magnitude and phase, between the positive-sequence voltages and currents at the regulator terminals. The equivalent circuit may be connected in the positive-sequence network of a system including the regulator for phase-angle control, to maintain the same relationships as the regulating transformer exhibits between positive-sequence quantities at the input and output terminals.

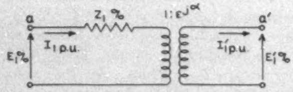
The equivalent circuit as derived has introduced one new conception, that of incorporating a phase-angle shift in the ideal transformer. The circuit including the ideal transformer is easy to handle analytically as a part of the positive-sequence network; but, unfortunately, it is not convenient at the present time to represent such a phase-shifting transformer on the network calculator, and the customary procedure is to include a transformer with ratio N and take the phase shift into consideration by analytical methods in the final results, or to make a special setup, using two power sources of the network calculator to absorb and reintroduce power at the proper phase positions, giving the effect of the phase shift. However, the equivalent circuit as given is very useful in visualizing the action of the regulating transformer as it affects positive-sequence quantities.



$$Z_1 = \frac{1}{N^2}\left(n_1^2 n_2^2 Z_{PS} + Z_{VW}\right)$$

(a)

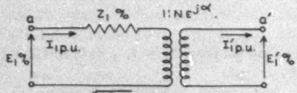
EXPRESSED IN OHMS



$$Z_1\% = \frac{\sqrt{N^2-1}}{N}\left(Z_{PS}\% + Z_{VW}\%\right)$$

(b)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES PROPORTIONAL TO N



$$Z_1\% = \frac{\sqrt{N^2-1}}{N}\left(Z_{PS}\% + Z_{VW}\%\right)$$

(c)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES THE SAME.

$$N = \sqrt{1+3n_1^2 n_2^2}$$

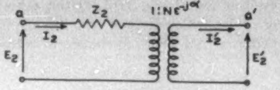
$$\alpha = \tan^{-1}\sqrt{3}\, n_1 n_2$$

Figure 4. Positive-sequence equivalent circuits for the phase-angle regulating transformer of figures 1 and 3

Percentage Representation Positive Sequence

Many investigators of analytical problems prefer to use a per-unit or percentage system of representation, in which all quantities such as voltage, current, kilovolt-amperes, and impedance, are expressed as a fraction or percentage of some base or normal value. In some cases, also, it is advantageous to make numerical calculations in per-unit or percentage terms. Consequently, it becomes desirable to express the equivalent circuits in similar notation.

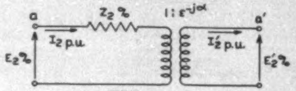
If the percentage or per-unit diagram is to be useful, it is essential that the base quantities used throughout be consistent. This is best achieved by selecting a minimum number of quantities and solving for the corresponding values of the remaining quantities. Thus, it is usually best to select a base power or kilovolt-ampere value for the entire system, and a voltage value for each metallically connected circuit, which is usually taken as the nominal voltage of that part of the system. It then becomes readily possible to express the basic equations of the equivalent circuit, such as equations 15, 17, and 18 of appendix I, in percentage values. The development is given in appendix II, for the phase-angle regulator previously discussed. Two sets of equations are derived; the first given by equations 24 and 25, for which the equivalent circuit is given in figure 4*b*; and the second given by equations 26 and 27, for which the equivalent circuit is given by figure 4*c*. The essential difference between the two cases lies in the voltages selected as the base voltages for the two sides of the regulating transformer.



$$Z_2 = Z_1 = \frac{1}{N^2}\left(n_1^2 n_2^2 Z_{PS} + Z_{VW}\right)$$

(a)

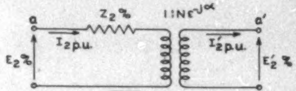
EXPRESSED IN OHMS



$$Z_2\% = \frac{\sqrt{N^2-1}}{N}\left(Z_{PS}\% + Z_{VW}\%\right)$$

(b)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES PROPORTIONAL TO N



$$Z_2\% = \frac{\sqrt{N^2-1}}{N}\left(Z_{PS}\% + Z_{VW}\%\right)$$

(c)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES THE SAME.

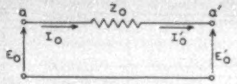
$$N = \sqrt{1+3n_1^2 n_2^2}$$

$$\alpha = \tan^{-1}\sqrt{3}\, n_1 n_2$$

Figure 5. Negative-sequence equivalent circuits for the phase-angle regulating transformer of figures 1 and 3

The maximum convenience in the use of the percentage system results when the base voltages on the two sides of the regulator are proportional to the transformer ratio. In this case the equivalent circuit is given by figure 4*b*, and the ideal transformer serves only to provide the phase-angle shift of current and voltage introduced by the regulator. This is normally possible when the regulating transformer is the only connection between the circuits on the two sides.

However, if the input and output circuits are directly interconnected by paths other than through the regulating transformer, the base voltages for the two sides of the regulator must be the same, and the equivalent circuit must be adjusted accordingly. This will be the usual case for circuits involving a regulating transformer for phase-angle control, since such apparatus is normally used to control the flow of power around a closed loop, or to divide power between parallel circuits. Under such conditions the equivalent circuit of figure 4*b* is no longer suitable and is replaced by the form shown in figure 4*c*, before connecting it into the system sequence network. From the figure it is seen that the only difference between the two circuits is the inclusion

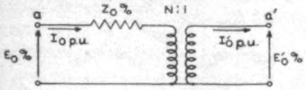


$Z_0 = n_1^2 n_2^2 Z_{PS} + Z_{VW}$

I_0 AND E_0 ARE NOT TRANSFORMED

(a)

EXPRESSED IN OHMS

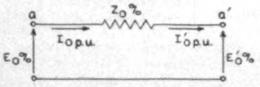


$N = \sqrt{1+3n_1^2 n_2^2}$

$Z_0\% = N\sqrt{N^2-1}\,(Z_{PS}\% + Z_{VW}\%)$

(b)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES PROPORTIONAL TO N.



$Z_0\% = N\sqrt{N^2-1}\,(Z_{PS}\% + Z_{VW}\%)$

(c)

EXPRESSED IN PER CENT, CIRCUIT BASE VOLTAGES THE SAME.

Figure 6. Zero-sequence equivalent circuits for the phase-angle regulating transformer of figures 1 and 3

of a transformation ratio in the idea transformer.

The above discussion points out the possibilities of confusion which are created when system sequence networks involving regulating transformers are set up using percentage quantities. To avoid this confusion, and to keep the regulator action in the different sequences clearly in mind, it is usually preferable to set up the sequence network in ohms, and to use volts, amperes, and ohms in the system analysis.

Negative-Sequence Equivalent Circuit

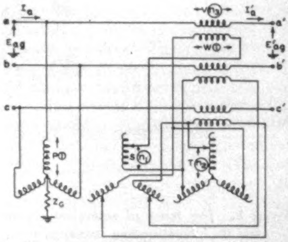
The negative-sequence equivalent circuit for the same regulating transformer may be derived by assuming negative-sequence currents to be circulated through the regulator diagram of figure 3. The derivation will not be given here in detail, since it is very similar to that just given for positive sequence. The results are given in figures 5*a*, *b*, and *c*, which show the negative-sequence equivalent circuits expressed in ohms and in per cent. Figures 5*b* and 5*c* correspond, respectively, to figures 4*b* and 4*c*, and the discussion with regard to the two forms of the positive-sequence equivalent circuit in per cent applies directly. It will be noted that the only difference between the positive- and negative-sequence equivalent circuits is in the phase-angle shift, the angle for negative sequence being the negative of that for positive sequence. This is a general rule for all power or regulating transformers; the positive and negative equivalent circuits are identical, except that the phase shift (if any is involved by the transformer) for negative sequence is negative to that for positive sequence. The impedances to positive and negative sequence are always identical; as, indeed, is the case for all static apparatus.

Zero-Sequence Equivalent Circuit

The zero-sequence equivalent circuit for the regulating transformer may be derived by assuming zero-sequence current to be circulated through the regulator. The derivation of the zero-sequence relationships is given in appendix III. Equations 39 and 46 reveal that neither zero-sequence current nor zero-sequence voltage are transformed by the regulating transformer; there is no transformer action on zero-sequence quantities, and the transformer acts merely as a reactor in the zero-sequence network. Again, it should be noted that Z_{PS} and the impedance to zero sequence, $Z_0 = n_1^2 n_2^2 Z_{PS} + Z_{VW}$, are functions of the tap position and Z_0 becomes Z_{VW} (the leakage impedance of the series transformer referred to the line-side winding) when the tap changer mechanism is in the neutral position. It should also be noted here that the zero-sequence impedance of the regulator has the same ohmic value viewed from either the input or the output circuit terminals. This is shown in the zero-sequence equivalent circuit given in figure 6*a*, which is set up to satisfy the equations in appendix III. There is no ideal transformer in this circuit, since zero-sequence current and voltage are not transformed.

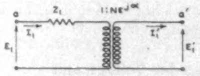
To obtain the zero-sequence equivalent circuit, expressed in per cent, the same procedure is followed as given in appendix II for positive sequence. Again two types are required, depending upon whether the base voltages on the two sides of the transformer can be chosen proportional to the ratio transformation of the regulator, *N*, or are required to be the same because the circuits are directly connected by a parallel path. To be consistent for any given problem, the base voltages used must be the same as used in the corresponding positive- and negative-sequence equivalent circuits.

The zero-sequence equivalent circuit, expressed in per cent, is given for the first case in figure 6*b* to satisfy equations 50 and 51. It is necessary to include an ideal transformer in this circuit, having an inverse transformation ratio to that in the positive- or negative-sequence



(a)

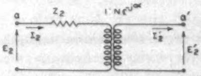
THREE PHASE EQUIVALENT CIRCUIT



$Z_1 = \frac{1}{N^2}(Z_{VW} + n_1^2 n_3^2 Z_{PS} + 3n_2^2 n_3^2 Z_{PT})$

(b)

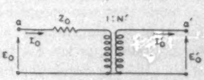
POSITIVE SEQUENCE, EXPRESSED IN OHMS



$Z_2 = Z_1 = \frac{1}{N^2}(Z_{VW} + n_1^2 n_3^2 Z_{PS} + 3n_2^2 n_3^2 Z_{PT})$

(c)

NEGATIVE SEQUENCE, EXPRESSED IN OHMS



$N' = 1 + n_1 n_3 = \sqrt{N^2 - 3n_2^2 n_3^2}$

$Z_0 = \frac{1}{(N')^2}\left[Z_{VW} + n_1^2 n_3^2 (Z_{PS} + 3Z_G)\right]$

(d)

ZERO SEQUENCE, EXPRESSED IN OHMS

$N = \sqrt{(1+n_1 n_3)^2 + 3n_2^2 n_3^2}$

$\alpha = \tan^{-1} \frac{\sqrt{3}\, n_2 n_3}{1 + n_1 n_3}$

Figure 7. Regulating transformer for voltage and phase-angle control, with the sequence equivalent circuits expressed in ohms

The parts ratios are:

$$\frac{U_V}{U_C} = \frac{U_P}{U_C} = \frac{n_3\sqrt{n_1^2 + 3n_2^2}}{N}$$

$$\frac{U_S}{U_C} = \frac{n_1 n_3}{N} \qquad \frac{U_T}{U_C} = \frac{\sqrt{3}\, n_2 n_3}{N}$$

equivalent circuits expressed in ohms, to maintain the proper relationships between per-unit zero-sequence currents and percentage zero-sequence voltages at the terminals. For the second case, in which the base voltages are the same, the equivalent circuit is given in figure 6*c*, to satisfy equations 52 and 53.

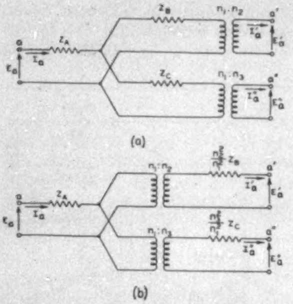


Figure 8. Two forms of equivalent circuits for the three-winding transformer

Regulator for Voltage and Phase-Angle Control

The example just given, in which zero-sequence voltage and current are not transformed with the same ratio as positive- and negative-sequence voltages and currents (or, as in the example, are not transformed at all) is quite common among regulating transformers. For regulating transformers used for voltage control alone, or for phase-angle control alone, it is found that zero-sequence current and voltage are transformed in the same ratio as positive, or are not transformed at all. In some regulating transformers for combination voltage and phase-angle control, it is found that zero-sequence quantities are transformed, but with a different ratio from that for positive- and negative-sequence quantities. In all cases, however, it is found that the zero-sequence equivalent circuit involves no phase shift, regardless of the phase shift introduced in the positive- and negative-sequence circuits.

A typical example involving different ratios is the regulating transformer for combined voltage and phase-angle control shown in figure 7*a*. The same notation is followed, to designate individual windings, as was used in figure 3. Z_G is the neutral impedance between ground and the neutral of the star-connected primary winding of the exciting transformer.

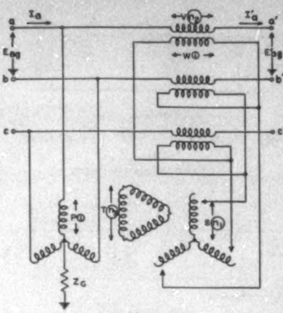
It will be observed that the exciting transformer in this case is a three-winding transformer, having the windings *P*, *S*, and *T* on the same core. The conventional equivalent circuit for such a transformer, assuming that the exciting impedance is infinite, has been developed a number of times before,[1] but is subject to the same limitations that characterize the circuit of figure 2*c*, namely, that the actual ratio of transformation is not provided for, and the terminals of the windings are not insulated from each other. These difficulties are again overcome by introducing ideal transformers of the proper turn ratios. Two forms of such equivalent circuits are shown in figure 8, *a* and *b*. It should be noted that the leakage impedances are broken up into components Z_A, Z_B, and Z_C, which are no longer arbitrary, but each is a definite function of the three leakage impedances between pairs of windings. Formulas for determining the components are given in the reference cited.[1]

Using this type of equivalent circuit for the exciting transformer, the positive-, negative-, and zero-sequence equivalent circuits for the entire regulating transformer can be derived by a process essentially similar to that already described. Space does not permit including the development, but the results are included in the figures.

The positive-sequence equivalent circuit expressed in ohms is given in figure 7*b*. To make certain the definitions of the quantities are clearly understood, they are given here (following the same convention for subscripts as used in the first example).

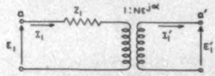
Z_{VW} = leakage impedance, in ohms, between the *V* and *W* windings as measured on the *V* winding with the *W* winding short-circuited
Z_{PS} = leakage impedance, in ohms, between the *P* and *S* windings as measured on the *P* winding with the *S* winding short-circuited and the *T* winding open-circuited
Z_{PT} = leakage impedance, in ohms, between the *P* and *T* windings as measured on the *P* winding with the *T* winding short-circuited and the *S* winding open-circuited

The negative-sequence equivalent circuit, expressed in ohms, is shown in figure 7*c*. The zero-sequence equivalent circuit expressed in ohms is shown in figure 7*d*. It will be noted from figure 7*d* that the transformation ratio for zero-sequence, *N′*, is not equal to the transformation ratio for positive-sequence, *N*. This results from the fact that the *T* winding carries no zero-sequence current, and would not carry zero-sequence current even if the neutral of the *T* winding were connected to ground.



(a)

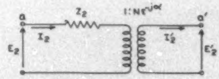
THREE PHASE EQUIVALENT CIRCUIT



$$Z_1 = \frac{1}{N^2}(Z_{VW} + 3n_1^2n_2^2Z_{PS})$$

(b)

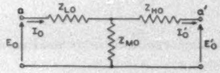
POSITIVE SEQUENCE, EXPRESSED IN OHMS



$$Z_2 = Z_1 = \frac{1}{N^2}(Z_{VW} + 3n_1^2n_2^2Z_{PS})$$

(c)

NEGATIVE SEQUENCE, EXPRESSED IN OHMS



$$Z_{MO} = Z_{PT} + 3Z_G$$

$$Z_{LO} = 0$$

$$Z_{HO} = Z_{VW}$$

(d)

ZERO SEQUENCE, EXPRESSED IN OHMS

$$N = \sqrt{1 + 3n_1^2n_2^2}$$

$$\alpha = \tan^{-1}\sqrt{3}\,n_1 n_2$$

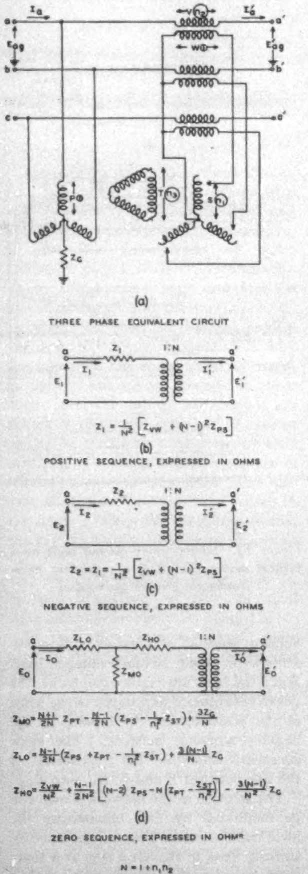
Figure 9. Regulating transformer for phase-angle control, with the sequence networks expressed in ohms

The parts ratios are:

$$\frac{U_V}{U_C} = \frac{U_P}{U_C} = \frac{\sqrt{3}n_1n_2}{N}$$

When the tap changer mechanism for voltage control, operating on the *S* winding, is in the neutral position, $n_1 = 0$, and zero-sequence current passes through the regulator without transformation. For this condition, regardless of the position of the tap changer for phase-angle control, the zero-sequence impedance of the regulator in ohms is Z_{VW}, the leakage impedance of the series transformer.

In order to conserve space, the corresponding equivalent circuits, expressed in per cent, have been omitted. There will be, of course, the two types, depending upon the choice of base voltages, just as in the previous example. As before,



a
b
c
a′
b′
c′
Ia
I′o
Eog
E′og
V
W
P
T
S
ZG
(a)
THREE PHASE EQUIVALENT CIRCUIT
Z1
1:N
I1
I′1
E1
E′1
$Z_1 = \frac{1}{N^2}\left[Z_{VW} + (N-1)^2 Z_{PS}\right]$
(b)
POSITIVE SEQUENCE, EXPRESSED IN OHMS
Z2
1:N
I2
I′2
E2
E′2
$Z_2 = Z_1 = \frac{1}{N^2}\left[Z_{VW} + (N-1)^2 Z_{PS}\right]$
(c)
NEGATIVE SEQUENCE, EXPRESSED IN OHMS
ZLO
ZHO
ZMO
1:N
IO
I′O
EO
E′O
$Z_{MO} = \frac{N+1}{2N} Z_{PT} - \frac{N-1}{2N}\left(Z_{PS} - \frac{1}{n_1^2} Z_{ST}\right) + \frac{3Z_G}{N}$
$Z_{LO} = \frac{N-1}{2N}\left(Z_{PS} + Z_{PT} - \frac{1}{n_1^2} Z_{ST}\right) + \frac{3(N-1)}{N} Z_G$
$Z_{HO} = \frac{Z_{VW}}{N^2} + \frac{N-1}{2N^2}\left[(N-2) Z_{PS} - N\left(Z_{PT} - \frac{Z_{ST}}{n_1^2}\right)\right] - \frac{3(N-1)}{N^2} Z_G$
(d)
ZERO SEQUENCE, EXPRESSED IN OHMS
$N = 1 + n_1 n_2$

Figure 10. Regulating transformer for voltage control, with the sequence equivalent circuits expressed in ohms

The parts ratios are:

$$\frac{U_P}{U_C} = \frac{U_S}{U_C} = \frac{U_V}{U_C} = \frac{N-1}{N}$$

the transformer ratio required in the ideal transformer for the first type will be $1/N$ times the ratio in the ohmic diagram. Thus for the first type of zero-sequence diagram expressed in per cent, the ratio will become $1:N'/N$, where N' and N are given in figure 7, instead of the ratio $1:N'$ as in the ohmic diagram. In every case it will, of course, be found that the transformation ratios in the second type of percentage diagram are the same as in the corresponding ohmic diagrams, since the base voltages used as reference are the same for both circuits of the transformer.

It is evident that the analysis of power systems involving such regulators is considerably more complex than for the simpler cases, but the use of ideal transformers again makes a solution readily possible.

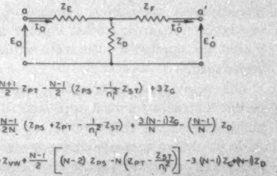
Phase-Angle Regulator Acting as Grounding Transformer

In what has preceded, the zero-sequence equivalent circuit has the same form as the positive-sequence equivalent circuit, except that there is no zero-sequence phase shift and the circuit may involve a different transformation ratio. In some cases the regulating transformer may also act as a source of ground current. When this is true, the zero-sequence equivalent circuit becomes entirely different. A typical example of this is the regulating transformer for phase-angle control, the circuit for which is shown in figure 9*a*. The positive- and negative-sequence equivalent circuits expressed in ohms are given in figures 9*b* and 9*c*. The same conventions as previously used for winding designations and leakage impedance definitions are used. Since the delta winding shown in the diagram is idle under balanced conditions, it has no effect on the positive- and negative-sequence equivalent circuits, and may be disregarded in these cases. Thus, no new problems are involved, and the derivation is omitted.

However, the delta has a decided effect upon the flow of zero-sequence current from lines to ground in the *P* winding, and the method used in deriving the zero-sequence equivalent circuit must be appreciably modified. The simplest procedure is to assume zero-sequence voltages to be applied to the input (*a*, *b*, *c*) terminals with the output (*a′*, *b′*, *c′*) terminals open-circuited. An equation is then found relating E_0 and I_0, and an equation relating E_0' and I_0'. The procedure is repeated with zero-sequence voltages applied to the output (*a′*, *b′*, *c′*) terminals with the input (*a*, *b*, *c*) terminals open-circuited, and a third equation written involving E_0' and I_0'. If, under these conditions, a fourth equation is written for E_0 as a function of I_0', the latter equation will be found convenient for checking the results of the first three equations. The form of the equations may suggest the type of equivalent circuit to be tried, such as figure 9*d*, and similar equations are written for the circuit selected, first by applying a voltage to the terminals *a*, and then to the terminals *a′*. If the circuit selected is a possible equivalent circuit, direct comparison between the equations derived for the actual transformer and for the equivalent circuit being tried will reveal values for Z_{L0}, Z_{M0}, and Z_{H0} which will satisfy the equations of the actual transformer. The required values for the case in question are given in the figure. It will be noted that there is no direct transformation of zero-sequence current and voltage; that is, I_0 and I_0', are not related by a fixed ratio. There is impedance coupling between the circuits, however caused by the *mutual* branch Z_{M0}, so that E_0 and E_0' are dependent upon the currents in both circuits, I_0 and I_0'.

Regulator for Voltage Control

The regulating transformer for voltage control shown in figure 10*a* has the equivalent circuits for positive and negative sequence shown in figures 10*b* and 10*c*. The equivalent circuit for zero sequence, expressed in ohms, may be derived following an analysis similar to that just described. Since zero-sequence transformation occurs, the simplest equivalent circuit to derive is that shown in figure 10*d*. This circuit is of the same form as that of figure 9*d*, except that it involves an ideal transformer as well as a shunt branch. This may be the most desirable form, but if the regulating trans-



a
a′
ZE
ZF
ZD
IO
I′O
EO
E′O
$Z_D = \frac{N+1}{2} Z_{PT} - \frac{N-1}{2}\left(Z_{PS} - \frac{1}{n_1^2} Z_{ST}\right) + 3Z_G$
$Z_E = \frac{N-1}{2N}\left(Z_{PS} + Z_{PT} - \frac{1}{n_1^2} Z_{ST}\right) + \frac{3(N-1)Z_G}{N} - \left(\frac{N-1}{N}\right) Z_D$
$Z_F = Z_{VW} + \frac{N-1}{2}\left[(N-2) Z_{PS} - N\left(Z_{PT} - \frac{Z_{ST}}{n_1^2}\right)\right] - 3(N-1)Z_G + (N-1)Z_D$

Figure 11. Alternate form of the zero-sequence equivalent circuit for the regulating transformer of figure 10

former is connected in a loop circuit, the reduction of the zero-sequence network for the system is simplified if there is no direct transformation of zero-sequence current and voltage, and consequently no ideal transformer. For such case, the equivalent circuit may be converted to the more useful form, without the direct transformation, shown in figure 11. The derivation of this equivalent circuit from that shown in figure 10*d* is given in appendix IV. It will be found that, for zero sequence, many regulating transformers can be represented by equivalent circuits of the type shown in figures 9*d* or 10*d*. Which type is most convenient will depend upon circumstances, but the derivation given in appendix IV shows that either form may be readily converted to the other, as needed, as long as Z_{M0} is not infinite.

Equivalent Circuits in Power System Analysis

In setting up the sequence networks of systems for analysis, the common procedure is to select some one circuit voltage as a base, and transfer the impedances of the various circuit elements from their actual values to equivalent values on the base voltage selected, by multiplying each impedance by the square of the ratio of the base voltage to the nominal voltage at the point where the circuit element is located. When regulating transformers of variable ratio are involved, this process often becomes confusing and difficult to follow. The process becomes even more complicated when zero-sequence quantities are not transformed, or have a different ratio of transformation from the positive- and negative-sequence quantities, because of the uncertainty regarding what voltage ratio should be applied to the zero-sequence impedance.

The equivalent circuits here outlined permit a straightforward approach to the problem, because they are set up to include ideal transformers where necessary, so that the circuit used is the exact equivalent of the actual transformer in every important respect, and may be substituted for it without making any conversions in the impedances of the other circuit elements. Then, where simplification is possible, the ideal transformers may be shifted from one location to another, with corresponding changes in circuit impedances, until in many cases the ideal transformers can be dropped out of the final diagram altogether. The process can best be described by means of two typical examples.

Figure 12*a* is the single-line diagram for a typical simple system, including a regulating transformer for voltage control, connected between points *a* and *b*. The sequence networks for the system, connected to represent a single-line-to-ground fault at *F*, are shown in figure 12*b*. The equivalent circuits of the regulator are of the type shown in figures 10*b* for positive sequence, 10*c* for negative sequence, and 11 for zero sequence.

To illustrate the method more fully, the delta-star step-up transformer bank is represented by equivalent circuits of the type described in this paper, in which ideal transformers are included to take care of the actual transformation ratio and the 30-degree phase shift introduced by the delta-star connection. It will again be noted that if the positive-sequence phase shift is +30 degrees, represented by ϵ^{j30}, the negative-sequence shift must be −30 degrees, represented by ϵ^{-j30}, in the ratios of the ideal transformers. As is well known in the theory of symmetrical components, the zero-sequence current will flow in the star side of the transformer, circulate in the closed delta, but will not flow out of the bank on the delta side, so that no ideal transformer is required in the zero-sequence circuit if the equivalent circuits are set up and viewed from bus *A* on the star side, as in this case.

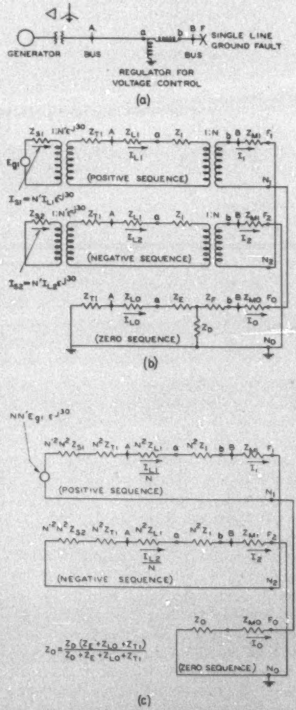

GENERATOR
BUS
A
a
b
B
F
BUS
SINGLE LINE GROUND FAULT
REGULATOR FOR VOLTAGE CONTROL
(a)
(POSITIVE SEQUENCE)
(NEGATIVE SEQUENCE)
(ZERO SEQUENCE)
$I_{S1} = N'I_{L1}\epsilon^{j30}$
$I_{S2} = N'I_{L2}\epsilon^{j30}$
(b)
$NN'E_{g1}\epsilon^{j30}$
$Z_0 = \frac{Z_D(Z_E+Z_{L0}+Z_{T1})}{Z_D+Z_E+Z_{L0}+Z_{T1}}$
(c)

Figure 12. Single-line-to-ground fault on a typical system including a regulating transformer for voltage control

The line impedance Z_{L1} and Z_{L0} for the line between *A* and *a* are included at their actual values, without any conversion, since all circuits are still represented on their actual voltage base. Since the lines are static equipment, the negative-sequence impedance is the same as the positive, and Z_{L1} is used in the negative-sequence network. The same comments apply for the impedances of the line between *B* and *F*, Z_{M1} and Z_{M0}.

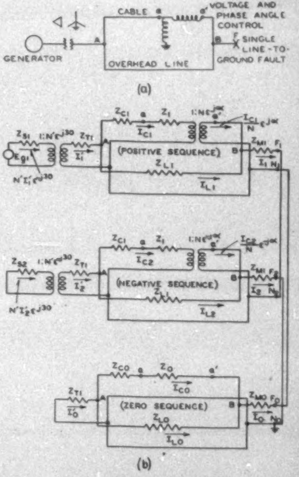


Figure 13. Single-line-to-ground fault on a typical system including a regulating transformer for phase-angle control

The solution of the network shown can be facilitated by first eliminating the ideal transformers. This may be done by shifting them to the left a step at a time. First the transformer of ratio 1:*N* is moved to the left past Z_1, Z_{L1}, and Z_{T1}. Of course, as this is done, the impedances must be multiplied by the square of the ratio, as shown in figure 12*c*, and the currents in the circuits affected become $1/N$ times their actual values, and the voltage *N* times as large as actual.

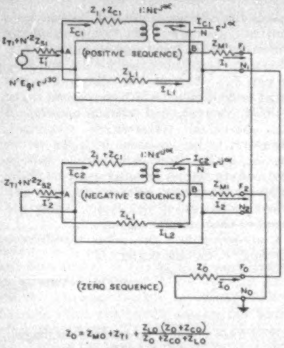


Figure 14. Simplified sequence networks for the system of figure 13

The ideal transformers of ratio $1:N$ may now be combined with the ones of ratio $1:N'\epsilon^{j30}$ and $1:N'\epsilon^{-j30}$ in the positive- and negative-sequence networks, respectively, to give new transformers of ratios $1:N'N\epsilon^{j30}$ and $1:N'N\epsilon^{-j30}$, respectively. These transformers may now also be moved to the left, past the impedances Z_{S1} and Z_{S2} of the generator. In the process the impedances are multiplied by $(N')^2N^2$, the square of the scalar ratio of transformation, but are not changed in phase angle, since the voltage and current are shifted in phase similarly, and no change results in their phase relations to each other. The voltages and currents are of course changed in magnitude, and also rotated in phase position, as indicated in the figure. When the ideal transformer reaches the generated voltage, E_{g1}, that too is altered in magnitude and phase, and the ideal transformer may now be dropped altogether, to give the final equivalent circuit shown in figure 12*c*.

In the zero-sequence network there were no ideal transformers, so the process described was not necessary. However, the two parallel circuits represented by Z_D and $Z_{T1}+Z_{L0}+Z_E$ can be combined to give Z_0 as shown.

The point to be emphasized is that, in the final network, Z_{L1} is multiplied by N^2, but in the zero-sequence network Z_{L0} is unchanged. The method outlined gives a straightforward approach to this result, but by methods in common use heretofore it is difficult to visualize the result and apply the proper conversion factors to Z_{L1} and Z_{L0}.

After the network of figure 12*b* is solved by straightforward methods, the ideal transformers can again be introduced, and moved to the right until their original positions are reached, the currents and voltages being converted to their actual values in the process. The phase currents and voltages can then be readily determined by combining the sequence quantities in accordance with the usual formulas.

Figure 13 represents a similar case except that two parallel circuits are involved, and, because one is underground cable and the other overhead line, a phase-angle regulator has been introduced to control the division of power The sequence networks for the fault condition are set up in figure 13*b* in the same way as before, using equivalent circuits involving ideal transformers. However, when simplification of the network is attempted, it is found impossible to shift the ideal transformers of ratios $1:N\epsilon^{j\alpha}$ and $1:N\epsilon^{-j\alpha}$ out of the closed loop. The other simplifications are carried out as before, giving the network of figure 14. Although this network is not as simple as in the preceding case, it may be solved analytically, making use of the properties of ideal transformers in writing the equations, or on a network calculator. In the latter case, with present equipment, a power source must be used to represent each winding of an ideal transformer involving phase shift, and the voltage and phase position of each must be adjusted by trial and error until the currents and voltages at the points representing the terminals of the ideal transformer bear the required relations to each other.

Summary

It has been shown how complicated regulating transformers can be represented by simple equivalent circuits, which fall into certain fairly well-defined types. By introducing the concept of ideal transformers to supplement the commonly used equivalent circuits for transformers, many problems can be more readily visualized and solved with much less chance for error. The method outlined can be used to derive suitable equivalent circuits for all the types of regulating transformers in common use, but obviously space does not permit including them here. However, the authors expect to publish these equivalent circuits in the near future.

Appendix I. Derivation of Positive-Sequence Equations for the Regulating Transformer Shown in Figure 3

Balanced positive-sequence currents are assumed to be circulated through the regulator. Since the windings are all symmetrical there will be no interaction between sequences, and the terminal voltages will consist of only a positive-sequence component. In the following development the vector operators a and a^2 will be used frequently. $a=\epsilon^{j120}=-1/2+j\sqrt{3}/2$, and $a^2=\epsilon^{j240}=-1/2-j\sqrt{3}/2$.

Thus at the left-hand terminals of figure 3:

$$\left.\begin{aligned} E_{ag} &= E_1 & I_a &= I_1 \\ E_{bg} &= a^2E_1 & I_b &= a^2I_1 \\ E_{cg} &= aE_1 & I_c &= aI_1 \end{aligned}\right\} \quad (1)$$

and at the right-hand terminals:

$$\left.\begin{aligned} E_{ag}' &= E_1' & I_a' &= I_1' \\ E_{bg}' &= a^2E_1' & I_b' &= a^2I_1' \\ E_{cg}' &= aE_1' & I_c' &= aI_1' \end{aligned}\right\} \quad (2)$$

Let e_p denote the voltage across the ideal transformer winding P, in the phase carrying I_A. Similarly let e_s denote the voltage of winding S in the corresponding phase, which causes n_1I_a'. Likewise, let e_v and e_w denote the voltages of the V and W windings, respectively, in the phase associated with I_a'. By applying Kirchhoff's voltage law to the diagram of figure 3,

$$\begin{aligned} E_{ag} = E_1 &= E_{ag}'+e_v+Z_{VW}I_a' \\ &= E_1'+e_v+Z_{VW}I_1' \end{aligned} \quad (3)$$

$$e_w = e_s \quad (4)$$

$$\begin{aligned} e_p &= E_{bg}-E_{cg}+I_AZ_{PS} \\ &= (a^2-a)E_1+I_AZ_{PS} \\ &= -j\sqrt{3}E_1+I_AZ_{PS} \end{aligned} \quad (5)$$

the last form of equations 3 and 5 resulting by substituting from equations 1 and 2, and making use of the properties of a.

From the required relations of the ideal transformers

$$e_s = n_1e_p \quad (6)$$

$$e_v = n_2e_w \quad (7)$$

$$I_A = n_1n_2I_a' = n_1n_2I_1' \quad (8)$$

Eliminating e_v, e_w, e_s, e_p, and I_A, by substituting first (8) in (5), (5) in (6), (6) in (4), then (4) in (7), and finally (7) in (3), gives

$$E_1(1+j\sqrt{3}\,n_1n_2) = E_1' + (n_1^2n_2^2Z_{PS}+Z_{VW})I_1' \quad (9)$$

At no load, $I_1'=0$, giving

$$E_1' = (1+j\sqrt{3}n_1n_2)E_1 \quad (10)$$

or, changing to polar form,

$$E_1' = \sqrt{1+3n_1^2n_2^2}\,\epsilon^{j\alpha}E_1 = N\epsilon^{j\alpha}E_1 \quad (11)$$

where

$$\alpha = \tan^{-1}\sqrt{3}n_1n_2$$

$$N = \sqrt{1+3n_1^2n_2^2}$$

Again, from the diagram:

$$I_A-I_B = I_C-I_C' = a(I_1-I_1') \quad (12)$$

Since I_A, I_B, and I_C are positive-sequence currents, $I_B=a^2I_A$ and

$$(1-a^2)I_A = a(I_1-I_1') = (1-a^2)n_1n_2I_1', \text{ from equation 8} \quad (13)$$

From (13)

$$I_1 = \left(1 + \frac{1 - a^2}{a} n_1 n_2\right) I_1'$$

$$= (1 - j\sqrt{3} n_1 n_2) I_1' = N\epsilon^{-j\alpha} I_1' \quad (14)$$

or

$$I_1' = \frac{1}{N} \epsilon^{j\alpha} I_1 \quad (15)$$

Since $1 + j\sqrt{3} n_1 n_2 = N\epsilon^{j\alpha}$, equation 9 becomes

$$N\epsilon^{j\alpha} E_1 = E_1' + (n_1^2 n_2^2 Z_{PS} + Z_{VW}) I_1' \quad (16)$$

Substituting from (15) and rearranging

$$E_1' = N\epsilon^{j\alpha} E_1 - \frac{1}{N}(n_1^2 n_2^2 Z_{PS} + Z_{VW}) \epsilon^{j\alpha} I_1$$

$$= N\epsilon^{j\alpha}\left[E_1 - \frac{1}{N^2}(n_1^2 n_2^2 Z_{PS} + Z_{VW}) I_1\right]$$

$$= N\epsilon^{j\alpha}[E_1 - Z_1 I_1] \quad (17)$$

where

$$Z_1 = \frac{1}{N^2}(n_1^2 n_2^2 Z_{PS} + Z_{VW}) \quad (18)$$

= impedance of the regulating transformer to positive-sequence, as viewed from the input (*a*, *b*, *c*) terminals

Appendix II. Derivation of the Positive-Sequence Equivalent Circuit in Percentage Quantities

Selecting the base quantities, let

U_N = base three-phase kilovolt-amperes for the system considered
E_N = base voltage of the input circuit line-to-neutral, expressed in volts
$E_N' = kE_N$ = base voltage of the output circuit, line-to-neutral, expressed in volts

The value to be assigned to *k*, that is, the ratio of the two base voltages, will be discussed later.

With voltage and kilovolt-amperes defined, the corresponding base currents become

$$I_N = kI_N' = \frac{1{,}000 U_N}{3E_N} \quad (19)$$

The impedance which will produce I_N when the input circuit base voltage is applied is the base impedance for that circuit, and becomes

$$Z_N = \frac{E_N}{I_N} = \frac{3E_N^2}{1{,}000 U_N} = \frac{E_{(L-L)}^2}{1{,}000 U_N} \quad (20)$$

where $E_{(L-L)}$ is the line-to-line voltage corresponding to the line-to-neutral voltage E_N. Similarly,

$$Z_N' = \frac{E_N'}{I_N'} = \frac{3(E_N')^2}{1{,}000 U_N}$$

$$= \frac{(E'_{(L-L)})^2}{1{,}000 U_N} = k^2 Z_N \quad (21)$$

Equation 17 is expressed in percentage quantities by multiplying by $100/E_N'$, or its equivalents, $100/kE_N$ and $100/kI_N Z_N$, giving

$$\frac{100E_1'}{E_N'} = \frac{N}{k}\epsilon^{j\alpha}\left[\frac{100E_1}{E_N} - \frac{100Z_1}{Z_N}\frac{I_1}{I_N}\right]$$

or

$$E_1'\% = \frac{N}{k}\epsilon^{j\alpha}(E_1\% - Z_1\% I_1 \text{ p.u.}) \quad (22)$$

where $E_1'\%$, $E_1\%$, and $Z_1\%$ denote E_1', E_1, and Z_1 expressed in percentage quantities, and I_1p.u. denotes I_1 expressed in per unit or as a fraction of its normal value. This combined notation, expressing voltage and impedance in per cent, and current in per unit, eliminates any factors of 100 in the final equation.

Similarly, equation 15 can be expressed in per unit by multiplying by $1/I_N'$, or its equivalents k/I_N, giving

$$\frac{I_1'}{I_N'} = \frac{k}{N}\epsilon^{j\alpha}\frac{I_1}{I_N}$$

or

$$I_1'\text{p.u.} = \frac{k}{N}\epsilon^{j\alpha} I_1 \text{ p.u.} \quad (23)$$

Although *k* is actually arbitrary, there are two values which are of special interest in connection with regulating transformers, namely, $k = N$ and $k = 1$. For $k = N$, equations 22 and 23 become

$$E_1'\% = \epsilon^{j\alpha}(E_1\% - Z_1\% I_1 \text{ p.u.}) \quad (24)$$

$$I_1' \text{ p.u.} = \epsilon^{j\alpha} I_1 \text{ p.u.} \quad (25)$$

The equivalent circuit which satisfies these equations is given by figure 4*b*. For $N = 1$, equations 22 and 23 become

$$E_1'\% = N\epsilon^{j\alpha}(E_1\% - Z_1\% I_1 \text{ p.u.}) \quad (26)$$

$$I_1' \text{ p.u.} = \frac{1}{N}\epsilon^{j\alpha} I_1 \text{ p.u.} \quad (27)$$

The equivalent circuit which satisfies these equations is given by figure 4*c*.

The value of $Z_1\%$ is obtained by multiplying equation 18 by $100/Z_N$, as suggested n equation 22, giving

$$Z_1\% = \frac{1}{N^2}\left(n_1^2 n_2^2 \frac{100Z_{PS}}{Z_N} + \frac{100Z_{VW}}{Z_N}\right) \quad (28)$$

It is customary to express the impedance of individual transformers in per cent, so that it would seem logical to express Z_{PS} and Z_{VW} directly in per cent of Z_N. However, the usual practice is to express the impedance in per cent on the kilovolt-amperes of the individual transformer as a base. In a regulating transformer such as this it is obvious that the kilovolt-amperes carried by either the series transformer or the exciting transformer is quite different from the kilovolt-amperes carried by the circuit. The current in the series transformer is the outgoing line current, but the voltage across the transformer winding is only that fraction of the line-to-neutral voltage supplied by the exciting transformer to produce the phase shift desired. Similarly, the exciting transformer has normal line-to-line voltage impressed, but carries a current equal only to $1/\sqrt{3}$ times the vector difference of the input and output currents. Hence the base impedance for Z_{PS} and Z_{VW} is not Z_N. Two entirely different values must be determined which correspond to the voltage, current, and kilovolt-amperes of the individual transformers concerned. However, to be consistent with the values for the entire circuit, the normal voltage and current values selected must be those applying when the voltage, current, and kilovolt-amperes of the input circuit are equal to their normal values.

Considering first the series transformer winding, *V*, its base current is

$$I_{NV} = \frac{1}{N} I_N \quad (29)$$

and its base voltage (no load) is, in magnitude,

$$E_{NV} = \sqrt{3} n_1 n_2 E_N \quad (30)$$

from appendix I by determining e_v when $E_1 = E_N$. The corresponding base impedance and base kilovolt-amperes become

$$Z_{NV} = \frac{E_{NV}}{I_{NV}}$$

$$= \frac{\sqrt{3} n_1 n_2 N E_N}{I_N} = \sqrt{3} n_1 n_2 N Z_N$$

or

$$\frac{1}{Z_N} = \frac{\sqrt{3} n_1 n_2 N}{Z_{NV}} \quad (31)$$

and the corresponding three-phase kilovolt-amperes becomes

$$U_V = \frac{3E_{NV} I_{NV}}{1{,}000} = \frac{3\sqrt{3} n_1 n_2 E_N I_N}{1{,}000 N}$$

$$= \frac{\sqrt{3} n_1 n_2}{N} U_N \quad (32)$$

Similarly, for the exciting transformer the base current in the *P* winding is, in magnitude

$$I_{NP} = \frac{n_1 n_2}{N} I_N$$

by considering equation 8 when $I_1 = I_N$. The voltage across the *P* winding is $\sqrt{3}E_N$, which is equal to the line-to-line voltage. Hence the base impedance becomes

$$Z_{NP} = \frac{E_{NP}}{I_{NP}} = \frac{\sqrt{3} N E_N}{n_1 n_2 I_N} = \frac{\sqrt{3} N}{n_1 n_2} Z_N$$

or

$$\frac{1}{Z_N} = \frac{\sqrt{3} N}{n_1 n_2}\frac{1}{Z_{NP}} \quad (33)$$

and the three-phase base kilovolt-amperes becomes

$$U_P = \frac{3E_{NP} I_{NP}}{1{,}000} = \frac{3\sqrt{3} n_1 n_2 E_N I_N}{1{,}000 N}$$

$$= \frac{\sqrt{3} n_1 n_2}{N} U_N \quad (34)$$

Comparing equations 32 and 34 shows that both the exciting transformer and the series transformer carry the same kilovolt-amperes under any given load condition.

The values of $1/Z_N$ may now be substituted in equation 28, giving

$$Z_1\% = \frac{1}{N^2}\left[\frac{n_1^2 n_2^2\sqrt{3}N}{n_1 n_2}\,\frac{100Z_{PS}}{Z_{NP}} + \sqrt{3}n_1 n_2 N\,\frac{100Z_{VW}}{Z_{NV}}\right]$$

$$= \frac{\sqrt{3}n_1 n_2}{N}\,(Z_{PS}\% + Z_{VW}\%)$$

$$= \frac{\sqrt{N^2-1}}{N}\,(Z_{PS}\% + Z_{VW}\%) \qquad (35)$$

where $Z_{PS}\%$ and $Z_{VW}\%$ are now the leakage impedances of the exciting and series transformers expressed in per cent on the kilovolt-amperes carried by those transformers when the circuit carries the base kilovolt-amperes, U_N (in all three phases). The ratio of the base kilovolt-amperes of the transformers to the base kilovolt-amperes of the circuit is obtained by rewriting equations 32 and 34 as

$$\frac{U_P}{U_N} = \frac{U_V}{U_N} = \frac{\sqrt{3}n_1 n_2}{N} = \frac{\sqrt{N^2-1}}{N} \qquad (36)$$

from appendix I.

Appendix III. Derivation of Zero-Sequence Equivalent Circuit for the Regulating Transformer Shown in Figure 3

Balanced zero-sequence currents are assumed to be circulated through the regulator. Because of symmetry the terminal voltages will likewise be balanced zero-sequence voltages.

Referring to figure 3,

$$\begin{aligned} I_a &= I_b = I_c = I_0 \\ E_{ag} &= E_{bg} = E_{cg} = E_0 \\ I_a' &= I_b' = I_c' = I_0' \\ E_{ag}' &= E_{bg}' = E_{cg}' = E_0' \end{aligned} \qquad (37)$$

Since zero-sequence current cannot flow into the corners of a closed delta winding without taps,

$$I_a - I_a' = I_b - I_b' = I_c - I_c' = 0 \qquad (38)$$

It immediately follows that

$$I_0 = I_0' \qquad (39)$$

that is, zero-sequence current is not transformed by the regulating transformer.

From the diagram, by Kirchhoff's voltage law,

$$E_0 = E_0' + Z_{VW}I_0 + e_v \qquad (40)$$

and

$$e_w = e_s \qquad (41)$$

$$e_p = E_{bg} - E_{cg} + I_A Z_{PS} = 0 + I_A Z_{PS} \qquad (42)$$

From the required relations of the ideal transformers

$$e_v = n_2 e_w \qquad (43)$$

$$e_s = n_1 e_p \qquad (44)$$

$$I_A = n_1 n_2 I_0' = n_1 n_2 I_0 \qquad (45)$$

Combining to eliminate e_v, e_w, e_p, e_s, and I_A gives

$$E_0 = E_0' + (n_1^2 n_2^2 Z_{PS} + Z_{VW})I_0$$

or

$$\begin{aligned} E_0' &= E_0 - (n_1^2 n_2^2 Z_{PS} + Z_{VW})I_0 \\ &= E_0 - Z_0 I_0 \end{aligned} \qquad (46)$$

where

$$Z_0 = n_1^2 n_2^2 Z_{PS} + Z_{VW} \qquad (47)$$

To express the above relations in per cent, the same process is used as in appendix II. Multiplying equation 39 by $1/I_N'$, or its equivalent, k/I_N, gives

$$\frac{I_0'}{I_N'} = \frac{kI_0}{I_N}$$

or

$$I_0' \text{ p.u.} = kI_0 \text{ p.u.} \qquad (48)$$

Similarly, multiplying equation 46 by $100/E_N'$, or its equivalent, gives

$$\frac{100E_0'}{E_N'} = \frac{1}{k}\left[\frac{100E_0}{E_N} - \frac{100Z_0}{Z_N}\,\frac{I_0}{I_N}\right]$$

or

$$E_0'\% = \frac{1}{k}\,(E_0\% - Z_0\% I_0 \text{ p.u.}) \qquad (49)$$

For the first case, when the base voltages are proportional to N, so that $k = N$, equations 48 and 49 become

$$I_0' \text{ p.u.} = NI_0 \text{p.u.} \qquad (50)$$

and

$$E_0'\% = \frac{1}{N}\,(E_0\% - Z_0\% I_0 \text{ p.u.}) \qquad (51)$$

For the second case, $k = 1$, and

$$I_0' \text{ p.u.} = I_0 \text{ p.u.} \qquad (52)$$

$$E_0'\% = E_0\% - Z_0\% I_0 \text{ p.u.} \qquad (53)$$

The value of Z_0, expressed in per cent, is found in the same way as for Z_1 in appendix II. In fact the only difference occurs in the coefficient, and the result is

$$Z_0\% = N\sqrt{N^2-1}(Z_{PS}\% + Z_{VW}\%) \qquad (54)$$

Appendix IV. Derivation of Equivalent Circuit With Shunt Branch and No Direct Transformation From Circuit With Shunt Branch and With Direct Transformation

Refer to figure 10*d* and figure 11, which are to be made equivalent. The two circuits will be equivalent if terminal measurements for the two circuits are identical. Consider first that the terminal a' in both circuits is open-circuited, and the voltage E_0 applied to the terminal a:

From figure 10*d:*

$$E_0 = I_0(Z_{L0} + Z_{M0}) \qquad (55)$$

$$E_0' = NI_0 Z_{M0} \qquad (56)$$

From figure 11:

$$E_0 = I_0(Z_E + Z_D) \qquad (57)$$

$$E_0' = I_0 Z_D \qquad (58)$$

Now consider that the terminal a in both circuits is open-circuited, and the voltage E_0' applied to the terminal a':

From figure 10*d:*

$$E_0' = -I_0' N^2 (Z_{H0} + Z_{M0}) \qquad (59)$$

$$E_0 = -NI_0' Z_{M0} \qquad (60)$$

From figure 11:

$$E_0' = -I_0'(Z_F + Z_D) \qquad (61)$$

$$E_0 = -I_0' Z_D \qquad (62)$$

If the two circuits are to be equivalent, by equating (56) and (58), or (60) and (62):

$$Z_D = NZ_{M0} \qquad (63)$$

Equating (55) and (57):

$$Z_{L0} + Z_{M0} = Z_E + Z_D$$

$$\therefore Z_E = Z_{L0} + Z_{M0} - Z_D = Z_{L0} - \frac{(N-1)}{N}\,Z_D \qquad (64)$$

Equating (59) and (61):

$$N^2(Z_{H0} + Z_{M0}) = Z_F + Z_D$$

$$\begin{aligned} \therefore Z_F &= N^2(Z_{H0} + Z_{M0}) - Z_D \\ &= N^2 Z_{H0} + (N-1)Z_D \end{aligned} \qquad (65)$$

Equations 63, 64, and 65 provide relationships existing between the branches of the circuit shown in figure 11 and the branches of the circuit shown in figure 10*d*, so that the two circuits are equivalent.

Reference

1. SYMMETRICAL COMPONENTS (a book), C. F. Wagner and R. D. Evans, McGraw-Hill Book Company, 1933.

Discussion

A. N. Garin (General Electric Company, Pittsfield, Mass.): The material presented in this very interesting and timely paper falls naturally into two distinct parts.

Seen from outside, the regulating transformer, consisting of two separate transformers properly interconnected and placed in a common tank, has the physical appearance of a single transformer. To be able to treat this combined unit as a single transformer in the analysis of the system it is necessary first to determine its terminal characteristics. Thus, the first problem is that of determining the characteristics of the combined unit from the characteristics of the two separate transformers forming the unit.

The second problem is that of representing the combined unit, which may now be treated as a single transformer, in the equivalent circuits of the system. I shall limit my discussion of this part of the paper to the observation that the difference in positive- and zero-sequence transformation ratios, the flow of zero-sequence currents through transformer windings without transformation, the various phase shifts, etc., are not exclusive prerogatives of regulating units consisting of two interconnected transformers, but often will be found in individual power transformers. The methods of analysis and representation described by the authors have, therefore, a broader significance and a wider field of application than they have indicated.

The procedure used for deriving the per-cent positive-sequence impedance of the circuit shown on figure 1 is straightforward, explicit, and does not presuppose any familiarity with the modern methods of transformer circuit analysis on the part of the reader. Since, however, several pages and 35 numbered equations are required to arrive at the value of the per-cent positive-sequence impedance of the very simple circuit of figure 1, it is obvious that the labor involved in deriving by this procedure the impedances of more complicated circuits, such for instance as the circuit of figure 7, must be prodigious.

The number and variety of regulating-transformer circuits, that are either in actual use or have been proposed, are quite impressive so that it is fortunate that no lengthy and complicated calculations are really required to determine their effective impedances. Thus the positive-sequence impedance of the regulating transformer of figure 1 may be obtained in the following manner. Assume that this transformer is designed to give a maximum quadrature voltage of ($r \times 100$) per cent and that it is desired to find the value of the positive-sequence impedance it will introduce in the system when operated on a tap connection giving a quadrature voltage of ($q \times 100$) per cent, where q may have any value from 0 to r. In terms of the system kilovolt-amperes, the kilovolt-amperes in the series transformer is given by $\frac{q}{\sqrt{1+q^2}}$, as indicated by the voltage vector diagram, and by the law of conservation of kilovolt-amperes the same figure must apply for the exciting transformer. The impedance introduced into the system, expressed in per cent at system kilovolt-amperes, is given by the sum of the impedances of the exciting and the series transformers, expressed in per cent at system kilovolt-amperes, multiplied by the square of the ratio of the kilovolt-amperes in each transformer to the system kilovolt-amperes.

If the per cent impedance of the exciting transformer, connected on the tap giving ($q \times 100$) per cent quadrature voltage, is denoted by $\%Z_{P-S}$ and the per cent impedance of the series transformer at the excitation corresponding to ($r \times 100$) per cent quadrature voltage is denoted by $\%Z_{V-W}$, the positive-sequence impedance of the combined unit may be written as:

$$\%Z_1 = \frac{q^2}{1+q^2}\left[(\%Z_{P-S}) + \frac{r^2}{q^2}\ (\%Z_{V-W})\right]$$

$$= \frac{1}{1+q^2}[q^2(\%Z_{P-S}) + r^2(\%Z_{V-W})]$$

This equation corresponds to equation 35 of the paper.

As another example, the positive-sequence impedance of the circuit of figure 7 may be derived as follows: let the regulating transformer be connected on taps giving ($p \times 100$) per cent in-phase and ($q \times 100$) per cent quadrature voltage and, as in the previous example, denote the maximum total voltage for which the series transformer is designed by ($r \times 100$) per cent. The kilovolt-amperes in various parts of the circuit in terms of the system kilovolt-amperes are readily seen to be:

Series transformer (by the voltage vector diagram)

$$\frac{\sqrt{p^2+q^2}}{\sqrt{(1 \pm p)^2 + q^2}}$$

Winding *P* of the exciting transformer (by the kilovolt-ampere conservation law)

$$\frac{\sqrt{p^2+q^2}}{\sqrt{(1 \pm p)^2 + q^2}}$$

Winding *S* of the exciting transformer (since it supplies only the in-phase component of the series transformer voltage)

$$\frac{p}{\sqrt{(1 \pm p)^2 + q^2}}$$

Winding *T* of the exciting transformer (since it supplies only the quadrature component of the series transformer voltage)

$$\frac{q}{\sqrt{(1 \pm p)^2 + q^2}}$$

Since the currents in windings *S* and *T* must be in time quadrature the impedance between these windings will not appear in the formula and the positive-sequence impedance of the combined unit may be written as

$$\%Z_1 = \frac{1}{(1 \pm p)^2 + q^2}[p^2(\%Z_{P-S}) + q^2(\%Z_{P-T}) + r^2(\%Z_{V-W})]$$

where all impedances are at system kilovolt-amperes, the upper sign before p is to be taken for boost and the lower for buck connections, $\%Z_{P-S}$ and $\%Z_{P-T}$ are for taps giving ($p \times 100$) per cent and ($q \times 100$) per cent voltage components, and $\% Z_{V-W}$ is taken at maximum excitation corresponding to ($r \times 100$) per cent series transformer voltage. Translated into ohms the above formula is identically the same as the formula appearing in figure 7*b* of the paper.

Formulas for effective values of zero-sequence impedances in terms of leakage impedances of the two transformers may be obtained by the same process, which need not be further enlarged upon since it has been presented to the Institute in 1936 in a paper entitled "Transformer Circuit Impedance Calculations" by K. K. Paluev and the writer.

In conclusion I should like to ask the authors a question that may have little bearing on the main subject of their paper, but is of considerable practical importance: do they consider the circuit of figure 7 to be a safe circuit from the viewpoint of the third harmonic?

Edward W. Kimbark (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): The authors have given a very clear derivation of the equivalent circuits of regulating transformers, and their results will prove valuable to any one who carries out, either by paper calculations or by use of a network analyzer, studies of power systems having such transformers. But there still remains the unsolved problem of how conveniently to represent on the network analyzer a regulating transformer for phase-angle control. The series impedance of the authors' equivalent circuit is readily represented, and the ideal transformer of complex ratio may be represented, as they mention, by two adjustable electromotive forces. As an alternative, one of the electromotive forces (the one which absorbs power) may be replaced by an impedance element. The disadvantage of any such scheme is the large number of adjustments to be made—adjustments which affect one another. Each electromotive force must be adjusted both in phase and in magnitude (or the impedance element which replaces one of them adjusted in both resistance and reactance), giving altogether four degrees of freedom. If studies are to be made of single-phase faults or other unbalanced conditions, then the equipment and adjustments of the positive-sequence network must be duplicated in the negative-sequence network, giving eight degrees of freedom. The adjustment of the regulating transformer itself, if it controls both ratio and phase angle, has only two degrees of freedom; or, if it controls phase angle alone, has but one degree of freedom; thus its network-analyzer representation has from two to seven superfluous degrees of freedom, which make the adjustments very laborious. The adjustments not only must be so made that they introduce the required phase shift and ratio of transformation into the two sequence networks, but they must also be made to satisfy two conditions which are satisfied automatically in the actual transformers, namely to give active and reactive powers on one side of the transformers equal to those on the other side.

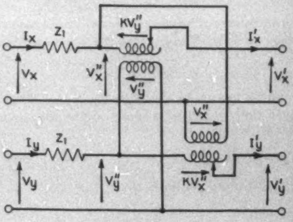


Figure 1

I wish to suggest a method of representing a regulating transformer which obviates these difficulties of adjustment. In the actual regulating transformer the phase shift is produced by taking voltage from one phase and introducing it in series with another phase. A three-phase representation could be used on the network analyzer. However, it is simpler to use a two-phase representation. A paper entitled "Two-Phase Co-ordinates of a Three-Phase Circuit," which I presented at the same meeting as the authors' paper (AIEE Trans-

ACTIONS, volume 58, 1939, pages 894–904), describes a set of substituted variables analogous to symmetrical components but different from them. Briefly, the positive- and negative-sequence networks of the method of symmetrical components are replaced by two other substitute networks, called the x and y networks, which jointly constitute a two-phase network equivalent to the original three-phase network after the zero-sequence currents and voltages have been abstracted from it. The equivalent circuit of the regulating transformer shown in figure 1 of the paper is given in terms of two-phase co-ordinates by figure 1 of this discussion. An adjustable voltage, proportional to the shunt voltage of each network, is introduced in series with the other network; and since under balanced conditions the x and y voltages are in quadrature, this cross connection effects an equal phase shift in each network as shown by the vectors of figure 2 of the discussion. With balanced negative-sequence conditions, the phase shift produced by the equivalent circuit is equal and opposite to that for positive-sequence conditions. Since unbalanced conditions are equivalent to the superposition of positive and negative sequence, the circuit also gives correct phase shifts under unbalanced conditions. Furthermore, the small inherent change in ratio produced by this type of regulating transformer when a phase-angle adjustment is made, is reproduced automatically by this equivalent circuit. For representing a regulating transformer with both phase-angle and ratio control, such as that shown in figure 7 of the paper, for example, autotransformers may be added to the output terminals of the x and y networks. Both these autotransformers and the adjustable series transformers may be gang-operated, so that the number of adjustments to be made on the network analyzer is the same as that on the actual transformer plus adjustment of the series impedances Z_1.

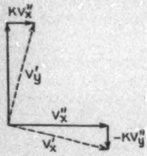


Figure 2

The disadvantage of the network-analyzer representation just presented, for a study of balanced conditions, is that two networks (the x and y networks) must be set up instead of one (the positive-sequence network), requiring additional apparatus and duplication of generator adjustments. For unbalanced conditions the same number of networks are required in either the symmetrical-component or the two-phase method, but in the latter method both networks contain generators. It is believed that in many cases the disadvantages stated will be more than offset by the ease of adjustment of the circuit representing the regulating transformer.

For paper calculations the symmetrical-component representation presented by the authors is definitely preferable, because the sequence networks of the transformer are independent.

Edith Clarke (General Electric Company, Schenectady, N. Y.): In volume 49, AIEE TRANSACTIONS, April 1930, page 819, I. H. Summers gave an equivalent circuit for a regulating transformer for voltage and phase-angle control. This circuit is not published under its own title, but is given as part of a discussion of the paper, "Inversion Currents and Voltages in Autotransformers," by A. Boyajian. Since one would not expect to find the equivalent circuit for a regulating transformer under this heading, it is not surprising that this valuable contribution has not received the attention it merits.

Mr. Summers' equivalent circuit is a static delta in which the sum of the three branch impedances is zero. With this circuit, a boost or buck in voltage and a forward or back shift in phase can be secured. Circuit base voltages may be the same or different, there is no restriction. When there is a shift in phase in the regulating transformer, the resistance of one of the branches of the equivalent delta must be negative. This makes the circuit inconvenient for use on an a-c network analyzer, but offers no difficulty in an analytic solution. It is an ideal circuit for analytic work with symmetrical components, since it can exactly replace the regulating transformer in each of the three sequence diagrams when exciting currents are neglected.

It may be well to point out that the symbol indicating division has been omitted between "Rated transformer kva" and "System base kva" in the equation (not numbered) for x.

It is customary to give transformer impedances in per cent based on their ratings; and for system studies, to express the impedances of the various circuits in per cent or per unit based on a chosen system kilovolt-ampere base and the base voltages of the individual circuits, determined at no load. The introduction of ohms and the use of base impedances is unnecessary, if the following principles are applied: (1) With exciting current neglected, the impedance of a two-winding transformer in per cent is the same referred to either side of the transformer when based on the kilovolt-ampere rating of the transformer and rated no-load voltages. (2) An impedance, in per cent on given kilovolt-ampere and voltage bases, can be expressed on new kilovolt-ampere and voltage bases if it is multiplied by the ratio of new to given base kilovolt-amperes and by the square of the ratio of given to new base voltage.

By inspection, the impedance to the current in the output circuit of figures 1 and 3, using the notation of the authors, is $(Z_{PS}\% + Z_{VW}\%)$ based on the voltage of the V winding and the kilovolt-ampere rating of the exciting and series transformers (assumed equal). Base current in winding V is base current of the output circuit; but base voltage of winding V is $\sqrt{3}n_1n_2E_n$, whereas base voltage of the output circuit is NE_n. The ratio of the kilovolt-amperes of the output circuit to the kilovolt-amperes of winding V is therefore the ratio of their base voltages. Expressed on the kilovolt-amperes and voltage of the output circuit, making use of principle (2) above, the impedance of the regulating transformer in per cent is

$$(Z_{PS}\% + Z_{VW}\%)\left(\frac{NE_n}{\sqrt{3}n_1n_2E_n}\right) \times \left(\frac{\sqrt{3}n_1n_2E_n}{NE_n}\right)^2 = (Z_{PS}\% + Z_{VW}\%) \times \frac{\sqrt{3}n_1n_2}{N}$$

This impedance has been determined for the output circuit, but it can be put in the input circuit as Z_1 per cent without change. When base voltages are proportional to N as in figure 4*b*, the same per-unit current flows in both circuits, and therefore it is immaterial on which side of the ideal transformer the per-cent impedance is placed.

The impedances of all regulating transformers cannot, of course, be determined so readily by inspection as that of figures 1 and 3. Figure 7, for example, with its three-winding transformers is more complex, but by using a per-unit equivalent circuit for the three-winding transformer, impedances for figure 7 and any of the other cases considered, can be determined directly in per cent.

It appears, therefore, that the authors could have reduced the length of their paper, and at the same time increased its usefulness as a reference, if they had determined the impedances of the various types of regulating transformers they have considered directly in per cent, instead of first in ohms as in appendix I, and then in per cent as in appendix II.

When the positive- and negative-sequence impedances in the other circuits of the system under consideration are equal, solution on the a-c network can be obtained by using α, β, and 0 components, described in "Problems Solved by Modified Symmetrical Components," *General Electric Review*, November and December 1938, or by using x, y, z components described in "Two-Phase Co-ordinates of a Three-Phase Circuit" by E. W. Kimbark, AIEE TRANSACTIONS, volume 58, 1939, pages 894–904.

Since the α and β voltages in a balanced system are at right angles to each other, in-phase and quadrature components of voltage corresponding to those of the regulating transformer can be automatically introduced into both the α and β circuits by the use of ideal transformers, and no readjustment is required during fault conditions. The connections of the α, β, and 0 (or the x, y, z) networks for various types of faults are given in the references cited above.

W. A. Lewis: Mr. Garin points out that many of the properties of regulating transformers described or derived in the paper are not exclusive properties of regulating transformers or transformer combinations, but are frequently found in individual power transformers. The authors have recognized this, of course, but the characteristics of individual transformers and their equivalent circuits have been covered by several authors in the past, and the effort in this paper was to discuss that phase of the general problem of transformer representation which had not been adequately covered heretofore. The methods of representation and analysis presented are believed to be adequate for attacking problems of all types, and assume little previous knowledge except Kirchhoff's laws and the elementary principles of two- and three-winding transformers.

Both Mr. Garin and Miss Clarke have criticized the length of the derivations. In so doing they have both implied that the desired objective was to derive the equivalent impedance of the regulating transformer in per cent, and that the steps given were believed by the authors necessary for that purpose. As a matter of fact the authors believe, for reasons stated in the paper, that less difficulty is encountered, and less confusion results, in complex cases, if the system study is carried out in ohms and volts rather than in per cent or per unit. The equivalent circuits have therefore first been derived in ohms and then converted to per cent for the benefit of that group who prefer to carry out numerical work in that form. Obviously, if the sole objective had been to derive the final results in per cent or per unit, it would have been much shorter to start with all quantities in that form and carry out the work directly in those units. For those who wish to carry all work in per cent, the principles enunciated by Miss Clarke will prove useful.

Again, the length of any derivation depends upon the starting point and the assumed knowledge. Both Mr. Garin and Miss Clarke give shorter derivations for some of the results of the paper, but in so doing, they make use of derived principles which are assumed to be familiar to the reader. This paper was written primarily for engineers engaged in occasional system studies, and the experience of the authors has indicated that the principles so easily assumed by the discussers are not widely known. For example, Mr. Garin assumes, in discussing figure 7, that, since the currents in windings S and T are in time quadrature, the impedance between them will not appear in the formula. He further assumes that the remaining impedances, when converted to the corresponding kilovolt-amperes, may be simply added. It is not at all apparent to the authors, and, we believe, to many of our readers, how these principles may be assumed without proof. In considering figures 9 and 10, for example, it is not at all apparent, without adequate derivation, that a single impedance is used for the positive-sequence impedance of figure 9*c* and that a T circuit must be used for the zero sequence of figure 9*d*. If the proofs for the principles so glibly stated to suit the case are supplied, and the results are worked out both for those who wish to work in ohms and those who wish to work in per cent, the authors believe that the derivations will not be substantially shorter than those given. Following the methods given, an engineer, not an expert in this particular field, confronted with a particular case, can proceed directly from fundamental principles to obtain the required equivalent circuit.

Mr. Garin asks if the authors consider the circuit of figure 7 safe from the standpoint of the third harmonic. The examples selected for the paper were chosen primarily to illustrate the points discussed, rather than because they were widely used in practice. The circuit of figure 7, composed of single-phase units or three-phase shell-type units, would not be recommended unless it was permanently connected to a low-impedance return path for zero-sequence fundamental and third-harmonic currents. Such a path might consist of a generator or synchronous condenser, having a low impedance to zero-sequence currents and permanently connected to the transformer, so that the transformer was not in service unless the machine was also operating. The machine neutral would also have to be connected to the transformer neutral with the minimum possible neutral impedance intervening.

If the regulating transformer of figure 7*a* were composed of small-size three-phase core-type units, it would probably be safe from the standpoint of third harmonic currents, but the zero-sequence circuit of figure 7*d* would be modified by the zero-sequence properties of the core-type unit.

Both Miss Clarke and Professor Kimbark have pointed out the possibilities of using other components than the usual positive-, negative-, and zero-sequence components. The components suggested have both advantages and drawbacks. For their components to be used, it is necessary to assume that the positive- and negative-sequence system impedances are everywhere equal. Where main transmission circuits are of primary importance, the characteristics of the generators and other rotating machines are usually predominant and this assumption is not allowable. Furthermore, in stability studies, where generating sources must be maintained separate, the representation of each source in two networks instead of one often introduces more complication than it saves. On the other hand, in studying the distribution system, the characteristics of the generators assume less importance, and the advantages of the method suggested may outweigh its disadvantages.

An Automatic A-C Potentiometer and Its Application to the Nondestructive Testing of Insulating Equipment

GEORGE KEINATH
MEMBER AIEE

THE importance of the measurement of dielectric loss for determining the quality of high-voltage equipment has been well known for a long time by the high-voltage-cable industry and its measurement has been included in the international regulations for acceptance tests of cables. It was obvious that the same method that had been applied successfully to cables could be used also for testing other high-voltage devices, such as transformers, bushings, etc.

Shortcomings of the Present Method of High-Voltage Testing With System Frequency

The short-time test with about twice the phase-to-phase voltage, as it is usually applied in routine tests, does not give any indication of what happens in the dielectric during the test. Many times the voltage stress during the test is so high that the object is partly damaged without, however, breaking down completely. This kind of test corresponds to a mechanical test during which the maximum load is applied without observing the deformation of the material as the test progresses.

Disadvantages of the Thomas-Schering Bridge When Used for Insulation Testing

The manual adjustment of the bridge takes too long a time for the usual high-voltage test lasting only about two minutes, half of which is used for raising the voltage from a low value to test voltage. To obtain the characteristic diagram of power factor versus voltage and time, it would be necessary to take within these two minutes at least ten readings of capacitance and power factor, and half of them at different voltages. Since this is impossible one has to be satisfied with a few readings at various voltages, with the highest one usually falling short of the maximum test voltage, because of the difficulty encountered in reading the instrument at the maximum value where it becomes too unsteady.

Principle of the New Automatic A-C Potentiometer

Automatic d-c potentiometers, with very high sensitivity, have been known for a long time. Their original designs require 30 to 40 seconds for the pen to go from one end of the chart to the other because of the step-by-step adjustment by a mechanical contactor, which is very similar to the manual adjustment of a potentiometer. The latest automatic d-c potentiometers are much faster and require only about two seconds for full-scale deflection, but are more complicated and, therefore, more expensive to manufacture.

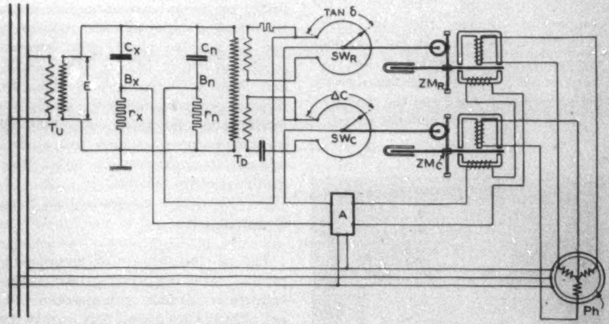


Figure 1. Schematic diagram of the automatic a-c potentiometer

The a-c potentiometer must be provided with *two* zero indicators, one for the active component of the current, and the other for the reactive component. It must also have two adjusting devices which may consist of variable resistors, inductors, or capacitors, whose settings indicate directly the measured value in a way similar to the slide-wire contact of the d-c potentiometer. Most of the recording d-c potentiometers in actual service have a galvanometer used as zero indicator and a continuously running motor and chopper-bar attachment which changes the position of the sliding contact when the value to be measured has changed. For considerable changes in value several steps are necessary for obtaining the final indication.

An a-c potentiometer developed by Geyger is equipped with an entirely new element, namely the *zero motor*, which serves both as zero indicator and as motor for adjusting the sliding contact. As there are two adjustments to be made, one for the active and one for the reactive component, we must have two zero motors, two sliding contacts, and two recorder charts.

Connection of the Potentiometer

Figure 1 shows schematically a simple arrangement for testing a high-voltage capacitor C_x by the voltage E from the testing transformer T_u. A standard capacitor C_n of negligible power factor is also connected to the testing transformer. In series with the capacitors are small resistors r_x and r_n, respectively. Furthermore, in parallel with C_n and C_x and their associated resistors there is a step-down transformer T_D with two secondary windings feeding two slide wires. One, SW_R, is in series with a resistor and the other, SW_C, is in series with a capacitor, resulting in currents and voltage drops which are in phase

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and in quadrature, respectively, with the high voltage E. The bridge is balanced when the two points B_x, B_n have the same potential. If this condition is not fulfilled, we may change either resistance or capacitance until equilibrium is established or, what is actually done, we add or subtract voltages from both slide wires and read the values of power factor tan δ and change of capacitance ΔC immediately from the position of the slide-wire contacts. This adjustment of active and reactive voltages in the bridge is done automatically by the two zero motors ZM_R and ZM_C. The voltage on the diagonal of the bridge, between the points B_x and B_n, is impressed on an amplifier A with power supplied by the line voltage. The output voltage of this amplifier is connected to the current coils of the two zero motors, whose voltage coils are connected through a phase shifter Ph to the phase-to-phase voltage and phase-to-neutral voltage, respectively. In this way one of the motors ZM_R gives a torque only with the active component of the amplified current, the other with its reactive component. Any voltage existing between the points B_x and B_n is amplified and feeds the motors, which move the contacts on the resistors SW_R and SW_C so that the voltage between the points B_x and B_n is more and more nearly compensated. When one of the components becomes zero, the corresponding motor stops at once without overrunning. The position of the contacts on SW_R and SW_C indicates directly the power factor tan δ and the change of capacitance ΔC of the material tested.

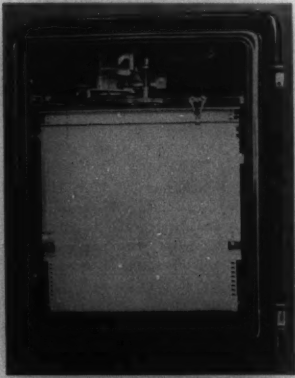


Figure 2. Recorder with built-in zero motor for moving the slide-wire contact and the pen

Actual connections of the a-c potentiometer are somewhat different from figure 1. Voltage for feeding the two slide-wire resistors SW_R and SW_C is not taken from a special step-down transformer but from a resistance in series with the standard capacitor C_n. The power required to supply the slide wires is so small that practically no additional error is involved. In some cases it may also be more convenient to replace the standard capacitor C_n by a voltage transformer of very high accuracy. The standard capacitor is then connected to the secondary of this transformer.

Properties of the Testing Equipment

Both motors run with variable speed. When the voltage difference between the points B_x and B_n is great, the speed is very high, about five revolutions per second, and becomes lower as balance is approached. Large deflections over the whole 250-millimeter (ten-inch) width of the paper are accomplished in not more than two seconds. The final setting of the contact and with it of the recorder pen is independent of line voltage and degree of amplification. Both factors influence only the speed but not the final results. The accuracy depends on the well-known elements of the a-c bridge, on the accuracy of the slide wires, the standard capacitor, the resistors r_x and r_n, and the phase angle between input and output voltage of the amplifier. The sensitivity is very high, the recorder giving the full deflection for two millivolts on the input; therefore, all precautions must be taken such as electric and magnetic shielding, as for other highly sensitive a-c bridges.

Construction

The new recorder is of utmost simplicity. The zero motors are watthour-meter elements with standard voltage coils and are special only in that the current coils have more than the usual number of ampere-turns. All other parts, including the slide wires, are the same as in other recorders of similar kind, but with the necessary shielding (figure 2). The sliding contact is connected with the pen and in this way continuous diagrams of power factor and capacitance are obtained from the recorders.

Sensitivity and Accuracy

The sensitivity may be the same as with any other a-c bridge, and is limited only by the degree of perfection obtainable in shielding the parts of the complete circuit, and by the accuracy of the standard resistors r_x and r_n and the capacitor C_n. For general testing work on bushings a range of five per cent for both power factor and capacitance is very useful, with changes of 0.1 per cent in power factor resulting in a deflection of 2.5 to 5 millimeters. For cable testing the range is adjusted to one per cent or even as low as 0.2 per cent, in order to detect sudden changes in capacitance or power factor in the order of 0.01 per cent or even lower. It must be understood, however, that these figures refer to sensitivity and not to accuracy. In this kind of test work it is not important to know whether the power factor is, say, 0.42 per cent or 0.43 per cent absolute, but it is important to know whether

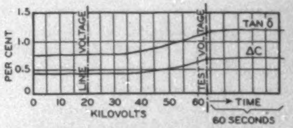


Figure 3. Change of capacitance and dielectric loss during the test of a bakelite-paper bushing for 20-kv rated voltage

Test voltage is 64 kv. Power factor is 0.75 per cent up to 32 kv and rises to 1.2 per cent at test voltage; a very good result. Change of capacitance is about 0.3 per cent between line voltage and test voltage. Capacitance increases at almost the same voltage as ionization begins

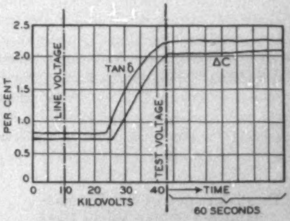
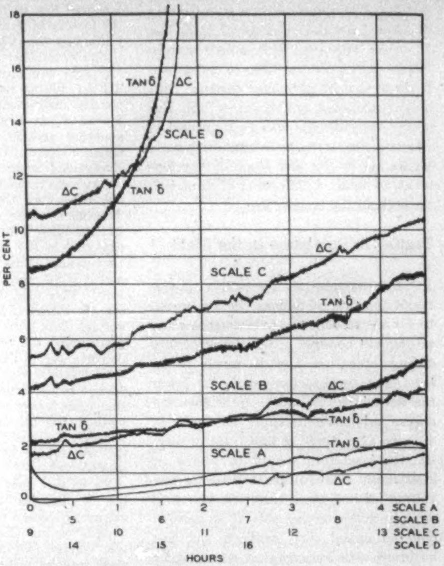


Figure 4. Same test on a bushing for 10-kv rated voltage and 42-kv test voltage

The initial value of power factor is almost the same, 0.8 per cent, but above 24 kv the ionization increases rapidly, the power factor at 43 kv being 2.25 per cent. The capacitance begins to increase at 26 kv; at 43 kv the increase is 1.2 per cent. Note slight, but definite, increase of both power factor and capacitance during the test there was a sudden change of 0.01 per cent during the test.

Figure 5. Testing of an old, compound-filled cable for $15\sqrt{3}$-kv rated voltage and 200 amperes rated current, with 50 kv and 300 amperes

(Copied from two separate diagrams for tan δ and ΔC, each 16 hours long)



Speed of paper chart 60 millimeters per hour. During the first half hour, power factor goes down from 1.2 per cent to 0.5 per cent due to temperature influences, capacitance changes only slightly, 0.1 or 0.2 per cent. After passing a minimum, both power factor and capacitance increase at the rate of about 0.5 per cent per hour. The diagram is first a thin line, but after more than one hour becomes thicker and rippled, showing deterioration of the cable during the test. With increasing losses the rise of tan δ becomes more rapid, the range has to be changed several times until final breakdown occurs with about 20 per cent power factor and increase of capacitance. Note the unsteady line in the last two-thirds of the test, a sure sign of the coming breakdown

Advantage of a Continuous Record of Power Factor and Capacitance

A continuous diagram gives much more information than spot readings plotted and connected to form a curve. It gives such details as small sudden changes in capacitance and power factor occurring when there is a partial breakdown in the dielectric. These changes might never be detected by spot readings.

Application of the A-C Potentiometer

A record is very useful, wherever dielectric losses are measured versus voltage or versus time with constant voltage. To record losses against voltage, we may move the paper not proportionally to time but proportionally to the voltage (which is a special feature of this form of an a-c potentiometer by moving the transport wheel of the paper instead of moving the recording pen) or one may raise the voltage of the testing transformer proportionally to time and move the paper chart in the usual way proportionally to time. The potentiometer is sensitive enough to give a reliable record with 20 per cent or even 10 per cent of the maximum voltage.

Testing of High-Voltage Equipment, for Example Bushings, Transformers, Cables, Capacitors

The voltage is raised proportionally to time up to test voltage and kept constant for the required time, usually one minute, while recording is done. Figures 3 and 4 show the results of test on two bakelite-paper bushings. Figure 5 gives the results of testing a high-voltage cable for 20 hours with seven times rated voltage and 50 per cent overcurrent. In the beginning of the curve, during the first three hours, the line is thin and even. It shows the variations of capacitance and dielectric loss with temperature. Changes in capacitance, not observed at all by other methods, may sometimes be even more significant than changes in power factor. After a few hours the line becomes thicker and rippled, indicating that the setting of the zero motor is no longer stable, which in turn shows that deterioration of the insulation has begun and the destruction of the cable has been started. The initial range was 0–6 per cent, but had to be changed to 6–12 per cent and later to 12–18 per cent. The increases of both power factor and capacitance are almost the same and rise rapidly until complete breakdown occurs after about 20 hours, without any damage to the instruments. Diagrams of this kind would provide excellent supporting data for any high-voltage test on cables as they give complete records of what is going on during the test.

Value of a Continuous Record in Comparison With Spot Readings

The continuous record, visibly written with ink on a paper chart, enables us to observe the whole test to see whether anything abnormal is going on. If the power factor of a bushing or of a transformer rises much faster than usual, the test may be stopped before the complete breakdown occurs, to give the device a better vacuum treatment for the next test.

The entire diagram gives a picture of the relative strength of the object under continuous high-voltage stress. If the ionization point is below the voltage between the lines, the device tested cannot be considered as good for continuous service. But if at test voltage the power loss is unusually small and not much greater than at line voltage, indicating that test voltage could be maintained indefinitely, the insulation is better than required. In this case either the insulation may be reduced or the same device may be used for the next rated standard voltage. By intensive study of current and voltage transformers in this manner it was possible to reduce their weight to such an extent that a complete set of three current transformers and three voltage transformers for 220-kv line voltage and 460-kv test voltage weighs only 12 tons, resulting in considerable reduction of the price and in possibilities of much larger applications than with the much more expensive earlier designs. The recording and measuring of power factor was the only means of insuring in the laboratory the absolute safety of operation which was confirmed later in many years of actual service. Not one of all these transformers developed any electrical defect in the last 12 years, although their weight was in many cases only one-fifth or even one-tenth of that of the earlier designs. Not only instrument transformers but also power transformers may be improved in this way, by testing all insulating parts separately in the first stage of development, to obtain a uniformity of insulation throughout the transformer.

Testing of Insulators in the Field

A test diagram taken with this apparatus at the time of delivery of the insulators is an excellent means of detecting any subsequent changes in insulating quality during operation and is much better than spot checks often made far below the actual line voltage. If it does not appear advisable to apply the full test voltage after three or five years of service, the insulators should be tested at least with line voltage. With a test voltage of not more than ten kv, as is used in many testing sets, it is possible only to detect wet bushings, but not bushings with ionization at some higher voltage. It is not possible within the scope of this paper to give a complete description of portable measuring sets, its purpose is only to attract attention to the much better information obtained from comparing diagrams for the insulator when new and after a period of service than from comparing figures. Even some temperature correction could be made automatically during the test, using temperature-sensitive standards for comparison.

It appears impossible to predict all the possible applications of the automatic a-c potentiometer. A number of European manufacturers are using it already in their test rooms, and some utility companies also are using it to test with it the high-voltage equipment prior to installation. In the opinion of the author it is in the interest of both manufacturers and users to complete the present method of test with a record which gives a clear picture of the uniformity and quality of the product. Potentiometer tests made as described herein give a very good indication of the subsequent behavior of the equipment in service with the possibility of checking changes of quality at any time later.

Discussion

George Keinath (in presenting the paper for discussion): In addition to my report, I should like to tell you something about the history of this development. Some 15 years ago the VDE (Verband Deutscher Elektrotechniker) raised the test voltage for 12-kv equipment from 30 to 42 kv. I did not like to have bigger and more expensive instrument transformers designed, I wanted just to improve the insulation by applying another, in my opinion better, vacuum treatment of the high-voltage coils. Everything seemed to go well, the test voltage was raised from 30 to 42 kv without any trouble for the short time of the test. Trouble, however, started plenty about two months later, when the same transformers exploded in the power stations, one after the other. They were compound-filled and it is not necessary to describe the picture. Very soon we found that the reason was the imperfect impregnation of the high-voltage coils, with the formation of nitrous gases inside the windings. It was easy to improve the process of impregnation, but with this experience I had lost all my confidence in the usual high-voltage test. At that time, however, 15 years ago, no better method for testing current and voltage transformers was existing, for testing with the a-c bridge at test voltage was impossible.

To be sure that the transformers would not be damaged by running with rated voltage, I made a type test with every new design, testing the transformer with the test voltage (42 kv for the 10-kv instrument transformer) not just one minute, but *eight hours*. This is certainly a very severe test, but I had no difficulty with any oil-insulated transformer and it was never necessary to increase the dimensions. All new current and voltage transformers were tested in this way, for 110-kv line voltage with 240 kv, for 240 kv with 460 kv, during eight hours. The result was the entire elimination of all failures in actual service—the bad thing, however, was that some of the customers wanted this test made for all transformers ordered by them.

Such an eight-hour test is very expensive and it will certainly not improve the insulating quality of the object under test. So I had to look out for a new method for suitable routine testing of transformers. This could be only a method which gave a record of the test—a diagram of the power factor and capacity change during the test. First we used a very sensitive wattmeter and later a vibrating mechanical rectifier and a d-c mirror galvanometer, and got a record of the active component of the capacity current versus voltage and versus time on photographic paper. Diagrams of this kind already had proved very successful for the development of new transformer designs, but the method was not good for routine testing of high-voltage equipment because the diagram had to be developed in the darkroom. So I decided six years ago to find a method to have the diagram written with ink on a paper chart during the short time of the ordinary voltage test, so that every change of capacity or power factor could be seen immediately and that the test could be stopped before the eventual breakdown was complete.

This recorder is described in my paper. It is for the greater part the work of my former colleague and collaborator Wilhelm Geyger, who during almost all his engineering time studied d-c and a-c potentiometers and their application for the most different purposes.

By using this recorder for testing all instrument transformers, and testing all their parts separately, I was able to reduce their dimensions more than anybody else tried to do before and afterward. I never did care for any "standards" regarding the dielectric stress as long as the power-factor record at test voltage was low, usually not more than two or three times the value at line voltage. Many designs originally intended for a certain line voltage have finally been used for 25 or 50 per cent higher rated voltage (of course with corresponding increase of flashover distance), after it turned out that the test voltage could be raised so far without any trouble. The total weight of a 110-kv current transformer which can be tested with 240 kv during eight hours and which will finally break down at 350 kv after this test was reduced by-and-by to less than 1,000 pounds.

The 220-kv current transformer was finally built with a weight of only 3,500 pounds; it was tested with 460 kv during eight hours and broke down with 650 kv after this test. Far more than 1,000 current transformers of this design are in actual service in Europe and there has never been a single electrical breakdown on them in the field, after they had been developed to have low power factor not only at the rated voltage, but also at test voltage. It seems to me that this proves well enough that the new method of testing corresponds with the practical experience. This method has been adopted also by other companies. The Allgemeine Elektrizitaets Gesellschaft uses a diagram drawn with the present recorder for advertising their voltage transformers and their good insulating qualities.

Eric A. Walker (Tufts College, Medford, Mass.): In the paper entitled "An Automatic A-C Potentiometer and Its Application to the Nondestructive Testing of Insulating Equipment," Doctor Keinath has made a very definite contribution to the power-factor testing of high-voltage insulation.

Engineers who must make power-factor tests have long realized the handicap imposed by the time required to balance a bridge circuit, especially if several guard or shield circuits must be balanced in addition to the principle bridge. Very often when testing used insulation, such as oil from circuit breakers or cellulose insulation which has been contaminated by moisture, the characteristics are not the same at the beginning of the test as when the test has been completed. For this very reason, wattmeter sets, with adequate shielding and correction factors to account for I^2R losses in the circuit, have considerable merit. By means of such a device a curve can be plotted point by point. In this paper, however, we are presented with a device which not only shortens the time required to make an observation but even automatically records that observation.

There are several points which the author might explain in more detail. First of all, must the standard capacitor C_n of the author's figure 1 have approximately the same capacitance as the object being tested? If not, what preliminary adjustments must be made before the potentiometer is ready to start a recording?

In a later paragraph the author speaks of an application to the testing of insulation in the field. We all know that most devices in the field which may be power-factor tested have one electrode grounded, such as the flange of a bushing or the tank of a transformer. This fact would require some changes in the wiring diagram of figure 1. Not only must the position of the ground shown in this figure be changed but the system of shielding must be modified. Moreover, unless a preliminary balance is made, which is what the author is trying to avoid, the shielding must be such that the capacitance which is then connected in parallel with the measuring means does not change as the physical position of the transformer, the high-voltage conductor, and other parts of the circuit are changed. This is one of the factors which makes the testing of grounded equipment rather difficult.

I would also like to ask the author what the response of the instrument will be if one attempts to make measurements in a strong electrostatic field? It is perhaps well-known, that when making dielectric loss measurements in the field, the currents induced in the circuit by electrostatic coupling between the object being tested and nearby energized wires are quite large. Although such currents may not seriously affect the capacitance balance of the bridge, their phase angle may be such that the power factor indicated is several times the true power factor. Indeed, negative power-factor indications are quite possible. Such erroneous values can hardly be avoided by shielding because it is highly impractical to attempt to shield a power transformer or circuit breaker in a congested substation.

In field testing, magnetic interference cannot be entirely neglected for one might be called upon to test a device which is near conductors carrying large currents.

One solution, of course, is to use a test voltage of different frequency from that of the interfering voltages or currents. Such a scheme is impractical for large devices because of the cost of generating equipment.

It is quite possible that further development is required before the device is adapted to the field testing of insulation, but there is no doubt about its value as a new laboratory tool.

P. L. Betz (Consolidated Gas, Electric Light and Power Company of Baltimore, Baltimore, Md.): The paper that has just been presented is of considerable interest to those engaged in dielectric testing. There are, however, several suggestions as to content that I would like to make. I have in mind a group of papers on dielectric testing which at first glance appears to give a complete story, yet, on closer consideration, one realizes that no paper in the group has given a complete circuit diagram which includes the shielding arrangements. I should like the author of this paper to include in his printed closing discussion a circuit diagram of his bridge that shows the actual shielding circuits, and the actual circuit means for supplying voltage for the two slide-wire resistors SW_B and SW_C. In the case of the shield circuits, what preliminary balancing is necessary and does this balance, made at a given voltage, apply for all of the other values of test voltage?

I would also like to ask the author for a comparison of the power factor measurements obtained with his bridge, and those obtained by means of a Schering bridge.

L. J. Berberich (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Doctor Keinath has described a very ingenious device for continuously recording power factor and capacitance change. In some insulation-testing applications it certainly has some advantage over the spot-reading procedures that must be used with the conventional bridges. The extent of the application of the device will, however, be strongly influenced by the cost of the equipment. We would appreciate it, therefore, if Doctor Keinath would give us some idea of the cost of the equipment necessary in order to transform a conventional power-factor bridge into one that records automatically.

In some of his earlier papers, Doctor Keinath suggested the use of automatic power-factor recording devices for testing the insulation on the stator windings of high-voltage generators. We believe that no power-factor method is satisfactory for testing the older machines, in which the contact between stator core and the outer surface of the coil insulation may not be definite. In the later machines, steps have been taken to make this contact definite and suppress all corona discharge that may form between the coil surface and stator slot and in these cases a test showing the power-factor behavior with voltage may have some value. In the older machines, however, a sharply rising power factor with voltage may be caused by either internal ionization or ionization between outer coil surface and slot. There is no way to distinguish between these and this is one of the problems that makes nondestructive testing of generator insulation difficult.

H. R. Richardson (Consolidated Edison Company of New York, Inc., New York, N. Y.): The recording a-c potentiometer described in Doctor Keinath's paper is of interest to the user of electrical insulating equipment in that continuous curves showing the trend and variations of power factor and capacitance with voltage or temperature against time are easily obtained. The record of momentary fluctuation of these quantities is of interest but I wonder if it is significant, especially in the case of oil- or compound-filled cables or bushings where small localized trouble spots are self-healing.

As this circuit is similar to the Dawes-Hoover high-voltage bridge with the exception of using a capacitor in the slide-wire circuit in place of a mutual inductor to obtain the quadrature balancing voltage, I presume that the shield and guard potentials must be adjusted in the same manner for this bridge as for the Dawes-Hoover bridge.

I would be interested in more detail as to the method of changing the range of this bridge. In particular, which resistor is changed and can this be done while the circuit is alive and the recorder in operation? Where the power factor is in the order of 20 per cent, as shown in figure 5 of the paper, would the accuracy of the bridge be seriously affected by this method of increasing the range?

Also, is a fixed phase shifter used to supply the fields of the zero motors? If so, what provision is made for a preliminary manual balance to assure the user that these fields are in the correct phase relation to the components of the unbalanced bridge current, especially as regards possible phase defect between line voltage and bridge detector voltage?

W. F. Davidson (Consolidated Edison Company of New York, Inc., New York, N. Y.): It was my good fortune during the past summer to have an opportunity to see in operation some of the recorders described in this paper. Of particular interest was a demonstration of the precision and speed of response. This was made by arranging a test sample so that small resistances might be inserted in series to increase the loss in power factor by a predetermined amount or so that small capacitances could be connected in parallel to cause an abrupt but definite change in the capacitances. For one set of tests, the full-scale power factor was two per cent while the scale in the capacitance element was such that a two per cent change represented the full range of the record. In both cases, the response was so rapid that it was impossible without the aid of special instruments to detect any time lag and at the same time there was no overtravel. Also, the power-factor record was entirely independent of the capacitance record and conversely the capacitance was influenced by changes in power factor.

My own experience during a good many years of testing insulation, particularly in high-voltage cables, has convinced me that a continuous record would reveal much information of decided value. This would be doubly true if the time scale could be sufficiently expanded so as to reveal rapid changes which escape detection when manually operated bridges must be resorted to.

A somewhat disturbing feature at the moment is the high cost of the equipment. Recently, I was given quotations on equipment to be imported from Germany and the figure was so high as to make it almost prohibitive, but this does not appear to be an unsurmountable obstacle.

A. J. Williams, Jr. (Leeds and Northrup Company, Philadelphia, Pa.): Doctor Keinath's solution to his problem is most interesting. As I understand it, with only a limited amount of time to make tests on each piece of equipment, he arranged to collect the maximum amount of information in the time that was available. He did this by placing a recorder on watch to make a record of the two principal factors throughout the whole time. Before this was done, the question might have been raised whether the extra information was helpful, but the end result obtained, namely, the production of smaller and more reliable equipment, seems to answer this question.

Doctor Keinath mentioned definitely that the gain of the amplifier does not affect the accuracy. It appears also that any phase shift in the amplifier would not affect the accuracy since at balance nothing comes through the amplifier anyway. This independence of phase shift is not general for power-factor measurement, but is definitely restricted to null measurements.

In connection with errors from the amplifier, it is possible that two or more upper harmonics from the bridge might, as a result of modulation in the amplifier, produce some input into the zero motor at fundamental frequency. This would result in a false shift in the balance position of the recorder. Although this type of error is not often encountered, the recorder described would be somewhat susceptible because of the high power level to which the amplification is carried, hence the greater chance for modulation.

It is most interesting that Doctor Keinath has been able to arrange his circuits so that balance of both components can be obtained by the use of slide-wires (rather than decade switches), which lend themselves to simple recorder construction.

In closing this discussion, I would like to ask:

(*a*). What was the approximate size of the slide-wires?

(*b*). What gearing was used between the zero motors and the slide-wires?

(*c*). Are the power-factor pen and capacitance pen in the same or separate recorders?

Frank C. Doble (Doble Engineering Company, Medford Hillside, Mass.): The paper by Doctor Keinath makes an interesting contribution along a line of investigation that needs attention in factory practice and one that should prove to be valuable to the manufacturers of electrical insulated equipment.

As a matter of general interest, it may be worth while to call attention to a statement in his paper under the subheading "Testing of Insulators in the Field," as follows:

> With a test voltage of not more than ten kv, as is used in many testing sets, it is possible only to detect wet bushings, but not bushings with ionization at some higher voltage.

This statement will bear careful analysis because "in the field" brings to mind routine tests on equipment as installed in operating position, whereas, the test described in the paper is more properly a manufacturer's test on new insulation at the factory.

In this country, nine years' experience with 10 kv for hundreds of thousands of field tests on insulation of all voltage ratings from 11 kv to 220 kv, inclusive, indicates that a 10-kv test is entirely adequate to show practically all forms of deteriorations, including the effects of moisture and corona, before they become immediate failure hazards.

It appears that in foreign practice there is a feeling that ten kv can not find, in time to prevent a failure, deterioration due to ionization, present only at or near operating voltage which might be several times ten kv. Without doubt, this belief is due to the fact that outside of the United States a very limited number of field tests on electric power equipment have been made at any voltage. Inexperience with actual ten-kv field tests accounts for the opinion still held by a few United States engineers that field tests at operating voltages are indispensable.

In American practice, there are numerous examples of actual failures on all operating voltages that were predicted by a ten-kv test. The case history of a 220-kv bushing failure which was predicted by a 10-kv test is available, together with similar data for all other operating voltages.

Moreover, ten-kv tests, properly applied to parts of a bushing, will reveal certain types of serious faults that would not be found by an over-all applied voltage up to or even greater than the normal operating voltage of the equipment under test.

We have records of approximately 1,000 tests made on solid-type bushings at least ten years old at a test voltage equivalent to 1½ times normal line to ground voltage. Very thorough investigation involving bushings dissected at the manufacturer's laboratory failed to disclose evidence of a serious failure hazard that would not be found by a ten-kv test in time to prevent failure in service.

A further point to consider regarding high-voltage testing in the field is that many extraneous losses inherent to high-voltage equipment but not causing deterioration might be present in a volume as great as a real defect that should be found. It appears that the disadvantage of these extra losses more than offset the apparent advantages of testing in the field at voltages higher than ten kv.

George Keinath: In answering Mr. Walker's question, I should like to say that the standard capacitor may have almost any capacity. Actually the following are used:

between
100 and 2,000 volts—50,000 micromicrofarads
1,000 and 20,000 volts— 2,000 micromicrofarads
5,000 and 250,000 volts— 100 micromicrofarads
20,000 and 500,000 volts— 50 micromicrofarads

There has to be a preliminary adjustment to bring the pen into the chosen range of the recorder, so that the width of the paper is utilized, as it should be, only for the expected *change* of capacity which is usually approximately the same as the power factor.

Of course the wiring diagram has to be different if the capacitor to be tested is grounded with one electrode.

The influence of electrostatic and electromagnetic fields on the bridge is the same as in any other bridge and for high sensitivity shielding has to be very effective. I was describing only a new device for an automatic a-c potentiometer recorder and all this could not help in the least to avoid difficulties as they arise with any a-c bridge.

Mr. Richardson is absolutely right if he says that with the measurement of power factor on a large object one cannot easily detect localized trouble spots. Even when the loss on this spot increases perhaps 100 per cent or more in comparison to the loss in the same area in the good parts of the object, this may be less than 0.1 per cent of the total loss in the capacitor.

Just as the shielding, this has nothing to do in principle with the automatic a-c potentiometer, but refers to the value of power-factor measurements in general. Actual experience, however, has shown that with a continuous record one can detect small partial breakdowns in the dielectric much better than by making spot tests. According to the sensitivity you have chosen, and which for a cable test well might be five inches for one per cent power-factor change, you can easily see a change of 0.01 per cent power factor by a sudden break of the line, at the same time mostly also on the capacity curve. On a hand-set bridge, however, you cannot rely on such small changes generally and you do not know whether you have a sudden break, or a slow rise which might be caused by increase of temperature. Naturally, if the trouble spot is too small in comparison with the whole capacitor area, you will not find it, even with the most sensitive recorder. On smaller objects, on bushings or transformers, partial breakdown due to defective spots is easily detected by a sudden break of the line. Some time ago, I published a number of diagrams taken with the photographic recorder which I already have mentioned.

The range of the recorder is changed by adjusting the tappings on the resistors on the grounded side. This is done while the circuit is alive and the recorder in operation. When the power factor is as high as 20 per cent, there is always not much accuracy left because the capacitor is very near breakdown. In these last minutes or perhaps hours of capacitor life you have a large amount of higher harmonics which take part in the development of heat. I cannot give data for the accuracy under such circumstances, but I think it would not be important if the actual value were 18 per cent instead of 20 per cent. It seems to me that the absolute value of power factor and capacity are always of much less importance than the recording of the smallest changes of same, hitherto not observed with spot readings.

In itself, the change of the range for power factor or capacity by adjusting the resistances, is as accurate as it should be, depending only on the accuracy of the resistors.

The phase shifter which supplies the current for the zero motors is set before the test. It is not necessary to readjust it during the test, even a considerable phase shift between the voltages in the three-phase supply, several degrees, could not affect the bridge.

I am much obliged to Doctor Davidson to give a report on his personal impression when he saw the recorder in my former laboratories in Berlin.

Replying to Mr. Berberich, I would say that a number of the recorders actually in use have been designed and delivered as a supplement to old a-c bridges with vibration galvanometers so that the recorder always may be checked with the old bridge wiring. For high voltage, for more than 200 kilovolts, the standard capacitor is the most expensive part of the whole equipment. The new parts comprise the recorders, amplifiers, and some resistors, the cost of same may be between $2,000 and $3,000, probably less, if they would be manufactured in this country.

I admit that some time ago I hoped to be able to get good information by the power-factor testing of generator coils. However, as I said in my paper, the power factor itself can never give by its numerical value any reliable indication of the quality of the insulation. Five per cent may be very good for a generator, but it is very bad for an oil-insulated coil. But, if you have either records of several generators of the same kind or of the same generator under different conditions, for example, after several years of service, you may be able to deduct important information on differences and changes of the power factor-voltage and capacity-voltage curves at approximately the same temperature. I have tried to develop a recorder which gives a continuous curve of the dielectric losses in a generator. I could not finish this work, because too many considerations had to be taken before a suitable generator in one of the big power stations of Berlin could be selected for this test, but I still think that this would give a very good picture of the temperature inside the windings of the generator, so that it could be run not to a maximum temperature, but to a maximum dielectric loss. Excessive dielectric loss destroys the insulation and brings down the breakdown voltage. The fact that it rises very fast with the temperature makes the measurement more sensitive than the measurement of temperature with thermocouples.

To answer Mr. Betz, the limits of accuracy in general are given by the a-c bridge; for the recorder they are given by the accuracy of the slide-wire calibration and by the accuracy of the mechanical parts used for the transmission. Perfect shielding is just as necessary as with any other a-c bridge and the necessary shielding is not typical for the automatic potentiometer, therefore I did not give details about the shielding. The voltage for the slide-wire is actually supplied from the standard capacitor, so that it is not necessary to have a step-down transformer for the test voltage.

Mr. Doble has objected to my statement that for high-voltage testing of bushings a higher voltage than ten kv should be used. There is no doubt about the excellent work Mr. Doble has performed with his method. He can claim that he has reduced to a great extent the number of failures due to bad bushings, but it seems to me, that only in exceptional cases he has tested the same bushings with a higher voltage too. I admit that I have no practical personal experience with tests in the field, but I have tested a number of bushings in the laboratory and we have found that some of them were perfect at ten kv, but had considerable ionization at line voltage. It seems to me that such bushings should be eliminated at once and not put in service until the deterioration is so much advanced that also the test at ten kv shows up the trouble. I do not think that there is much difference in behavior, besides the fact that a part of the humidity evaporates after bringing the bushings into the warm laboratory.

It seems to me that a diagram with varying voltage gives much more information than a single point, especially when it is compared with the diagram at the time of delivery. I think that Mr. Doble's method could be very much improved in this way. If it should come to the weight of the testing equipment, I should say, that I had developed on the other side testing transformers with a very small weight, so that even an equipment for 150- or 200-kv test voltage could easily be transported with a light truck. I am sorry not to agree with Mr. Doble when he states that the dissecting of bushings never disclosed failures that would not also be found by a ten-kv test. We found corona traces on 60-kv bushings with a perfect 10-kv record.

I am much obliged to Mr. Williams to tell me that even a phase shift in the amplifier does not affect the accuracy of the measurement. The zero motor is practically tuned to the fundamental wave, because the current in the voltage coil has an almost pure sine shape and does therefore not respond to the higher harmonics eventually produced by the amplifier. We have made special tests and found that even 100 per cent third and fifth harmonic did not change the indication.

To answer Mr. William's questions:

(*a*). The slide-wire is of the toroid type and about six inches long.

(*b*). The transmission between the slide-wire and the motor is done by a metallic ribbon.

(*c*). The two zero motors and the two pens may be either in one or in two recorders, depending on the width of the recording diagram desired. Actually both types of recorders are used.

Two-Phase Co-ordinates of a Three-Phase Circuit

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IN RECENT years there has been an increasing interest in the use of substituted variables in the analysis of unbalanced three-phase circuits and machines. The best known and most widely used of the substituted variables are symmetrical components, introduced by Fortescue[1] in 1918. In the method of symmetrical components the actual currents and voltages of the three phases of a three-phase circuit are replaced by the zero-sequence, positive-sequence, and negative-sequence currents and voltages, and, furthermore, the three-phase circuit itself is replaced for purposes of analysis by three fictitious single-phase circuits known as the sequence networks. This method has achieved extensive use in the analysis of polyphase machinery and in the making of fault studies on three-phase power systems. Another example of substituted variables is furnished by the direct-axis and quadrature-axis quantities as defined by Park[2] in 1929, which have greatly facilitated the mathematical analysis of salient-pole synchronous machines.

This paper deals with a new set of substituted variables, which will be found simpler to use than symmetrical components in the analysis of certain types of unbalanced three-phase circuits. The new variables are related[3] both to symmetrical components and to the direct- and quadrature-axis quantities, but are different from either. They were used by Park and Skeats,[4] by Clarke, Weygandt, and Concordia,[5] and by Stanley[6] in the analysis of transient problems; and have been developed by Miss Clarke[7,8] for use in steady-state problems. They have been called "modified symmetrical components" or "α-β components"; but the author believes that they are of sufficient importance to merit a more distinctive name, and proposes the name "two-phase co-ordinates (or components)" as an appropriate one, because the three-phase circuit to be analyzed is replaced by an equivalent two-phase circuit and a single-phase circuit similar to the zero-sequence network.

The purpose of this paper is to provide a comprehensive and systematic derivation of the equations and equivalent circuits in two-phase co-ordinates of all the usual three-phase circuit elements such as series and shunt impedances, open circuits and short circuits, transformer banks, and transmission lines. This material, which will be found in the appendix, is preceded by a short discussion of the properties of two-phase co-ordinates and by several examples of their application.

Definition of Two-Phase Components

The two-phase components of current (I_x, I_y, I_z) and of voltage (V_x, V_y, V_z) are defined as follows in terms of the phase currents (I_a, I_b, I_c) and the phase voltages (V_a, V_b, V_c):

$$\left.\begin{aligned} I_x &= (2I_a - I_b - I_c)/3 \\ I_y &= (I_c - I_b)/\sqrt{3} \\ I_z &= (I_a + I_b + I_c)2/3 \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} V_x &= (2V_a - V_b - V_c)/3 \\ V_y &= (V_c - V_b)/\sqrt{3} \\ V_z &= (V_a + V_b + V_c)/3 \end{aligned}\right\} \quad (2)$$

Note that the expression for I_z differs from that for V_z by a factor 2.

If equations 1 and 2 are solved for the phase quantities in terms of their two-phase components, the following expressions are obtained:

$$\left.\begin{aligned} I_a &= I_x + {}^1/_2 I_z \\ I_b &= -{}^1/_2 I_x - (\sqrt{3}/2)I_y + {}^1/_2 I_z \\ I_c &= -{}^1/_2 I_x + (\sqrt{3}/2)I_y + {}^1/_2 I_z \end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned} V_a &= V_x + V_z \\ V_b &= -{}^1/_2 V_x - (\sqrt{3}/2)V_y + V_z \\ V_c &= -{}^1/_2 V_x + (\sqrt{3}/2)V_y + V_z \end{aligned}\right\} \quad (4)$$

The current and voltage symbols in equations 1 to 4 may represent either instantaneous values (real numbers) or steady-state values (complex numbers or vectors); however, the use of steady-state values only is considered in this paper.

Relation of Two-Phase Components to Symmetrical Components

By substituting into equations 1 and 2 the usual expressions for phase currents and voltages in terms of their symmetrical components, we obtain the following expressions for two-phase components in terms of symmetrical components:

$$\left.\begin{aligned} I_x &= I_1 + I_2 \\ I_y &= j(I_1 - I_2) \\ I_z &= 2I_0 \end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned} V_x &= V_1 + V_2 \\ V_y &= j(V_1 - V_2) \\ V_z &= V_0 \end{aligned}\right\} \quad (6)$$

where subscripts 0, 1, 2 denote zero- positive-, and negative-sequence components, respectively. The x current and voltage are equal to the sum of the positive- and negative-sequence components, and the y current and voltage are equal to the difference of the positive- and negative-sequence components, multiplied by j. The z voltage is the zero-sequence voltage, but the z current is twice the zero-sequence current.

Imagine a balanced set of three-phase currents of positive sequence. Their negative-sequence component, I_2, is zero. Their two-phase components are given by equations 5 as $I_x = I_1$ and $I_y = jI_1$, which denote balanced two-phase currents of phase order y, x. (The phase angle between I_x and I_y is the same as that between the conventional positive directions of the x and y axes of a rectangular co-ordinate system.) If, on the other hand, the three-phase currents are of negative sequence, their two-phase components are given by equations 5 as $I_x = I_2$ and $I_y = -jI_2$, which denote balanced two-phase currents of phase order x, y.

The symmetrical components in terms of two-phase components are:

$$\left.\begin{aligned} I_0 &= I_z/2 \\ I_1 &= (I_x - jI_y)/2 \\ I_2 &= (I_x + jI_y)/2 \end{aligned}\right\} \quad (7)$$

$$\left.\begin{aligned} V_0 &= V_z \\ V_1 &= (V_x - jV_y)/2 \\ V_2 &= (V_x + jV_y)/2 \end{aligned}\right\} \quad (8)$$

Relation of Two-Phase Components to Direct- and Quadrature-Axis Quantities

The direct-axis current, i_d, and the quadrature-axis current, i_q, are defined as follows in terms of the instantaneous

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[1] For all numbered references, see list at end of paper.

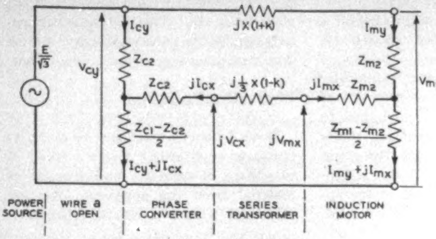


Figure 1. Equivalent circuit in two-phase co-ordinates of a phase converter taking single-phase power and supplying three-phase power through a series transformer in wires b and c to a three-phase induction motor (problem 3)

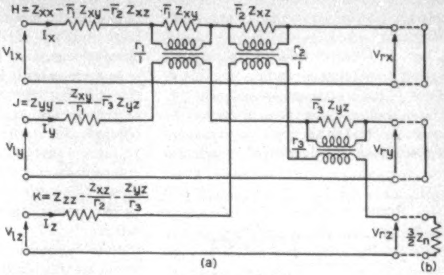


Figure 2. Equivalent circuit for series impedances (a), and, when joined to (b), for wye-connected shunt impedances

armature phase currents (i_a, i_b, i_c) of a synchronous machine:

$$\left.\begin{aligned} i_d &= (2/3)[i_a \cos\theta + i_b \times \\ &\quad \cos(\theta - 120°) + i_c \cos(\theta + 120°)] \\ -i_q &= (2/3)[i_a \sin\theta + i_b \\ &\quad \sin(\theta - 120°) + i_c \sin(\theta + 120°)] \end{aligned}\right\} \quad (9)$$

where θ = electrical angle between the magnetic axis of phase a and the direct field axis, varying with time. If we put $\theta = 0$ in equations 9, the expressions for i_d and $-i_q$ become equal respectively to those for I_x and I_y in equations 1. A like relation holds for voltages.

The direct- and quadrature-axis currents, i_d and i_q, give magnetomotive forces on two axes in space quadrature and fixed with respect to the field structure, while the two-phase components of current, I_x and I_y, give magnetomotive forces along axes in space quadrature and fixed with respect to the armature. If the two-phase components, I_x and I_y, of given three-phase currents, I_a, I_b, and I_c, flow in the windings of a symmetrical two-phase machine, they produce a space-fundamental magnetomotive force proportional to that produced by the given three-phase currents flowing in the windings of an equivalent three-phase machine. Furthermore, the electromotive forces induced in the windings of a two-phase machine by a given space-fundamental magnetic flux density are proportional to the two-phase components, E_x and E_y, of the electromotive forces, E_a, E_b, and E_c, induced in the windings of the equivalent three-phase machine by the same flux density.

Physical Interpretation of Two-Phase Components

Examination of equations 3 brings out the physical meaning of the two-phase components of current. Suppose that current component I_x is present alone, I_y and I_z being absent. The actual currents are then found by setting I_y and I_z equal to zero, which gives:

$$I_a = I_x \qquad I_b = I_c = -I_x/2 \qquad (10)$$

That is, I_x is a current which flows out on conductor a and returns equally divided between conductors b and c.

Again, suppose that I_y is present alone. Putting $I_x = I_z = 0$ in equations 3 gives:

$$I_a = 0 \qquad I_c = -I_b = (\sqrt{3}/2)I_y \qquad (11)$$

That is, I_y is a current flowing out on conductor c and back on conductor b. It does not flow in a.

I_z, of course, has the well-known characteristics of zero-sequence current.

Measurement of Two-Phase Components

The two-phase components of current and voltage in a three-phase circuit may be measured by ammeters and voltmeters connected to the three-phase circuit through groups of instrument transformers, the connections and ratios of which may be determined from inspection of the coefficients in equations 1 and 2. Since the coefficients are real, no impedances need be employed, as in the measurement of positive- and negative-sequence quantities, to shift phase.

If I_z is known to be absent, I_x is equal to I_a and may be read on an ammeter in line a. V_x is proportional to the reading of a voltmeter connected from line a to the mid-point of an autotransformer or drop wire connected between lines b and c. V_y is proportional to the voltage between lines b and c.

Equations 3 and 4 indicate how the phase currents and voltages can be read directly by combining electrically the two-phase components existing in networks set up on a calculating board.

Expression for Power in Terms of Two-Phase Components

The total complex power (usually called "vector power") of a three-phase circuit is given by

$$P + jQ = I_a \operatorname{conj} V_a + I_b \operatorname{conj} V_b + I_c \operatorname{conj} V_c \qquad (12)$$

On substituting equations 3 and 4 into 12, the expression for complex power of a three-phase circuit is obtained in terms of two-phase components:

$$P + jQ = (3/2)(I_x \operatorname{conj} V_x + I_y \operatorname{conj} V_y + I_z \operatorname{conj} V_z) \qquad (13)$$

The power is seen to be invariant except for the presence of the constant factor 3/2. This degree of invariancy is necessary for the correct representation of short circuits or open circuits on a three-phase network by connections between the substitute networks.

Substitute Networks

The substitution of new currents and voltages for the three-phase currents and voltages in every branch of a three-phase network in accordance with equations 3 and 4 may be extended to embrace the substitution of three new single-phase networks for the original three-phase network. The new networks are the x network, wherein I_x and V_x exist, the y network, wherein I_y and V_y exist, and the z network, wherein I_z and V_z exist. They are analogous to the positive-, negative-, and zero-sequence networks used in the method of symmetrical components. They may be set up to scale on a calculating board, or used merely as diagrams for paper calculation.

The x and y networks may be regarded as jointly constituting a two-phase network equivalent to the given three-phase network with its zero-sequence or z quantities removed.

For a balanced three-phase network having no polyphase rotating machinery, the x, y, and z networks are independent. The x and y impedances are equal to each other and to the positive- and negative-sequence impedances (which are also equal to each other in this case). The z impedances are one-half the corresponding zero-sequence impedances. Even in the case of polyphase rotating machinery it is sometimes regarded as sufficiently accurate to assume the positive-sequence impedance equal to the negative-sequence impedance, and in such cases it is permissible to assume that the x and y networks are independent. To be more accurate, however, an inequality in the positive- and negative-sequence impedances is equivalent to a coupling between the x and y networks, in the nature of a nonreciprocal mutual impedance, $Z_{xy} = -Z_{yx}$, which is difficult to represent on a calculating board.

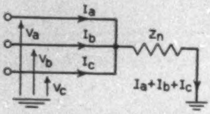


Figure 3. Wye connection

If the three-phase network contains balanced three-phase electromotive forces of positive phase sequence, then the x and y networks contain electromotive forces of equal magnitude, those in the y network leading those in the x network by 90 degrees. Ordinarily the z network contains no generated electromotive forces.

The self- and mutual impedances of the substitute networks and the connections between the networks corresponding to any given impedances and connections of the three-phase network or a portion thereof may be found by the following process: (1) Draw a diagram of the three-phase circuit element. (2) Write equations expressing the relations between the phase voltages, currents, and impedances. (3) By substituting equations 3 and 4 into the equations mentioned in step 2, obtain an equal number of equations giving the relations between the two-phase components of current and voltage and the impedances. (4) Find an equivalent circuit satisfying the equations obtained in step 3. Such circuits can always be found if the use therein of ideal transformers of real or complex ratio is allowed. In the appendix there are presented the results of this process for a large number of different three-phase circuit elements.

In some cases it is simpler to consider the different two-phase components of current to flow separately, and then to compute for each the resulting phase voltages and from them the two-phase components of voltage and the impedances. This method is used in the appendix to find transmission-line impedances.

In those cases in which the x and y networks are independent, the following simple rule may be used to find their self-impedances: Z_{xx} is two-thirds of the impedance between line a and lines b and c joined together. Z_{yy} is one-half of the impedance between lines b and c.

Comparison of Two-Phase Co-ordinates and Symmetrical Co-ordinates

The method of two-phase co-ordinates has two advantages over the method of symmetrical co-ordinates: First, as shown by inspection of the equivalent circuits developed in the appendix, the y network is independent of the x and z networks (though the latter two are usually coupled) in every case in which the represented three-phase circuit is static and is symmetrical with respect to phase a. Second, even if the static three-phase circuit is not symmetrical with respect to phase a, the substitute networks are coupled by reciprocal mutual impedances, which are readily represented on a calculating board, and never by nonreciprocal mutual impedances as is the case in the method of symmetrical co-ordinates.

The disadvantages of the method of two-phase co-ordinates are, first, that the x and y networks are coupled nonreciprocally in the case of balanced rotating machines having unequal positive- and negative-sequence impedances, whereas the positive- and negative-sequence networks of such machines are independent; and, second, that both the x and y networks contain generated electromotive forces, whereas in the method of symmetrical co-ordinates only the positive-sequence network contains them.

The method of two-phase co-ordinates is thus most useful in the analysis of unbalanced static three-phase circuits which are symmetrical with respect to one phase. In this category fall many transformer connections (such as delta-delta with one transformer different from the other two, vee-vee, vee-reversed vee, tee-tee, and Scott), open circuits, short circuits, single-phase loads, etc. The analysis is particularly simple if the connections are also such that zero-sequence current cannot flow.

Illustrative Problems

Several examples will now be given to illustrate applications of the method of two-phase co-ordinates and the use of material from the appendix. For applications to fault studies, see reference 7.

Problem 1

Statement. A common device for indicating the phase rotation of a three-phase circuit consists of two lamps and a reactor connected in star. For one phase order one lamp is brighter than the other and for opposite phase order the second lamp is brighter than the first. Show which lamp is brighter when a positive-sequence voltage is applied to the device, and calculate the current in each lamp if its resistance is 100 ohms, the impedance of the reactor, 0 + j100 ohms, and the applied voltage, 110 (line to line).

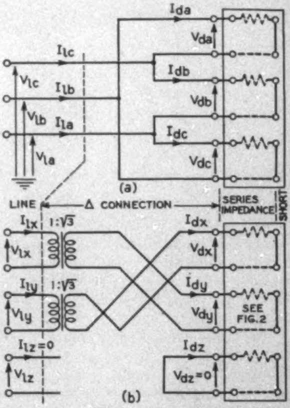


Figure 4. Delta connection of impedances (a) and its equivalent circuit (b)

Qualitative Analysis. It is advisable to denote the phases in such manner that the circuit is symmetrical with respect to phase a; hence the reactor will be called phase a, and the lamps, b and c.

The path of I_x consists of the reactor in series with the parallel combination of two lamps; the impedance of this path is predominantly inductive, and therefore I_x lags behind E_x by a large angle. The path of I_y, being through the two lamps in series, is resistive; hence I_y is in phase with E_y.

For balanced positive-sequence voltage, E_1, the two-phase components of voltage are equal in magnitude and are in time quadrature, E_y leading; that is, $E_y = jE_x = jE_1$. As a result of this phase relation between E_x and E_y and of those between E_x and I_x and between E_y and I_y, it follows that I_x and I_y are approximately in phase opposition.

The expressions for the lamp currents, I_b and I_c (using equations 3 and noting that $I_z = 0$) are proportional to $I_x + \sqrt{3}I_y$ and to $I_x - \sqrt{3}I_y$, respectively. Inasmuch as I_x and I_y are nearly in opposition, it is obvious that I_c is larger than I_b, and that lamp c is brighter than lamp b if the phase sequence is positive (abc).

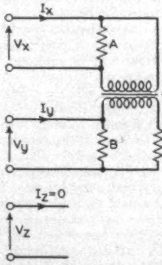


Figure 5. Equivalent circuit for shunt impedances connected in delta or in ungrounded wye

Calculations

$E_x = E_1 = E_a = 110/\sqrt{3} = 63.5$ volts,
$E_y = jE_x = j63.5$ volts,
$Z_a = j100$ ohms, $Z_b = Z_c = 100$ ohms.

Refer to cases 14 and 9 of appendix. From equations 9b,

$Z_x = (1/3)(2Z_a + Z_b) = (100 + j200)/3$ ohms, and $Z_y = Z_b = 100$ ohms
$I_x = E_x/Z_x = 63.5 \times 3/(100 + j200)$
$= 0.38 - j0.76$ ampere
$I_y = E_y/Z_y = j63.5/100 = j0.64$ ampere
$I_z = 0$ because the neutral of the star is isolated
$I_b = {}^1\!/_2(-I_x - \sqrt{3}\, I_y + I_z)$
$= {}^1\!/_2(-0.38 + j0.76 - j1.10)$
$= -0.19 - j0.17$ ampere
$|I_b| = 0.26$ ampere
$I_c = {}^1\!/_2(-I_x + \sqrt{3}I_y + I_z)$
$= {}^1\!/_2(-0.38 + j0.76 + j1.10)$
$= -0.19 + j0.93$ ampere
$|I_c| = 0.95$ ampere

PROBLEM 2

Statement. A certain three-phase 60-cycle overhead line, 1.0 mile long, consists of three number 0000 seven-strand copper cables spaced two feet apart in a plane. There are no transpositions and no ground wires. What impedances should be connected in series with the wires to equalize the voltage drops of the three wires when the line currents are balanced?

Solution. Compute the line impedances Z_{xx} and Z_{yy} by substituting into equations 34e the following data:

$R_a = R_b = R_c = 0.303$ ohm per mile, $D_{aa} = D_{bb} = D_{cc} = 0.0158$ foot, $D_{ab} = D_{ac} = 2$ feet, $D_{bc} = 4$ feet, $\omega = 2\pi \times 60$ radians per second. This gives $Z_{xx} = 0.303 + j0.559$ and $Z_{yy} = 0.303 + j0.669$ ohm. In addition, $Z_{xy} = 0$.

In order for balanced line currents to give balanced voltage drops, the line impedances Z_{xx} and Z_{yy}, must be equal. To equalize them Z_{xx} must be increased by $j0.110$ ohms. From case 7 of the appendix we find that an impedance Z in wire a is equivalent to $2Z/3$ in network x, but has no effect on network y. Hence the line impedances may be equalized by adding an impedance $1.5 \times j0.110 = j0.165$ ohm in series with the center wire.

Since $Z_{xz} = j0.028$ ohms, a small V_z drop is produced by balanced line currents, tending to unbalance the line-to-ground, but not the line-to-line voltages.

PROBLEM 3

Statement. A three-phase induction motor, connected to a single-phase line (on terminals b and c) and running without shaft load, is used as a phase converter to supply three-phase power to a second induction motor, which runs loaded. Investigate the efficacy of a series transformer with negative mutual inductance, connected in wires b and c of the line between the phase converter and the motor, in reducing the voltage unbalance at the motor terminals.

Analysis. The single-phase line may be considered as a three-phase line, wire a of which is open. The three-phase circuit then consists of the following parts in the order named: (1) single-phase source of voltage E connected between wires b and c, (2) open circuit in wire a of line, (3) phase converter in shunt with line, (4) series transformer in phases b and c of line, (5) induction motor in shunt with line. The equivalent circuit for two-phase components is made up of the equivalent circuits for the several parts, connected in the same order. These circuits are found in the following sections of the appendix: phase converter and induction motor, cases 2 and 14; open circuit, case 11; series transformer, case 10. The single-phase source is represented by an electromotive force $E/\sqrt{3}$ in network y. The equivalent circuit resulting from the combination of the several parts may be simplified in two ways: (1) omission of network z, since I_z cannot flow; (2) omission of the two transformers of ratios $1:j$ through which networks x and y are coupled, with the understanding that the currents and voltages in the x network now represent jI_x and jV_x instead of I_x and V_x. The circuit thus simplified is shown in figure 1, with notation of the impedances as follows: Z_{c1} and Z_{c2} are the positive- and negative-sequence impedances of the phase converter; Z_{m1} and Z_{m2}, the same for the motor; X is the self-reactance of the transformer coils in wires b and c; and k is the coefficient of coupling, making the mutual reactance $-kX$.

Knowing numerical values of these impedances, it is now an elementary network problem to compute the motor terminal voltages jV_{mx} and V_{my}; and if $jV_{mx} = V_{my}$ the voltages are balanced. It should be noted that $(Z_{c1} - Z_{c2})/2$ is several times as large as Z_{c2} for an unloaded machine and that motor voltage jV_{mx} is lowered by the drop $2Z_{c2}jI_x$. It is now clear that the function of the series transformer is to add impedance to network y without adding an appreciable amount of it to network x, thus lowering V_{my} to the already lowered value of jV_{mx}. If, for simplicity, we assume $k = 1$, the impedances added to networks x and y are, respectively, 0 and $j2X$. To produce balanced motor voltage, jX should equal Z_{c2} as a first approximation.

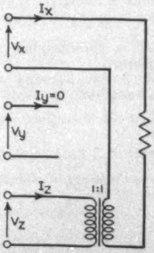


Figure 6. Equivalent circuit for shunt impedance Z connected line to neutral or ground

The equivalent circuit of figure 1, with suitable modifications, may be used to investigate the effect of other devices, such as a series capacitor in wire a, tapped autotransformers, etc., on the motor terminal voltages.

The solution of this problem by symmetrical components is given by Lyon.[10]

Conclusion

Though prognostication is uncertain, it seems probable that the chief application of the method of two-phase co-ordinates will be in the field of power distribution, with its single-phase loads, unsymmetrical transformer connections, untransposed lines, and mixtures of three-phase and two-phase circuits; whereas the chief application of the method of symmetrical co-ordinates has been in the fields of transmission and of polyphase machinery.

At any rate, a man who is confronted with a problem on unbalanced three-phase circuits should consider which method is best suited to his particular problem—the use of the actual three-phase currents and voltages, of symmetrical components, of two-phase components, or of some other substitution of variables devised to fit the specific problem.

Appendix. Equations and Equivalent Circuits for Two-Phase Components Corresponding to Various Three-Phase Circuit Elements

General Remarks

Notation

V_{la}, V_{lb}, V_{lc} = line-to-ground voltages of wires a, b, c at left-hand side of the circuit element, volts. The positive direction of voltage rise is from ground to line as indicated by the arrows in figure 3

V_{lx}, V_{ly}, V_{lz} = corresponding two-phase components

V_{ra}, V_{rb}, V_{rc} = line-to-ground voltages at right-hand side of circuit element, volts

V_{rx}, V_{ry}, V_{rz} = corresponding two-phase components

For shunt elements subscripts l and r are omitted

I_{la}, I_{lb}, and I_{lc} = line currents in wires a, b, c, entering left-hand side of the circuit element, amperes

I_{lx}, I_{ly}, I_{lz} = corresponding two-phase components

I_{ra}, I_{rb}, I_{rc} = line currents leaving right-hand side of circuit element

I_{rx}, I_{ry}, I_{rz} = corresponding two-phase components

For shunt elements or series elements subscripts l and r are omitted

For transformer banks subscripts p and s are used instead of l and r, and the positive direction of all currents is toward the transformers as indicated by the arrowheads in figures 9 to 12, inclusive

Z = impedance, ohms. Various subscripts are used and the significance in any particular case is explained in the text for that case or is apparent from the equations or figures thereof

r = transformer turns ratio

Other symbols are defined in the text for particular cases.

Units. It should be noted that all voltages, currents, and impedances, both in the equations and in the diagrams, are in volts, amperes, and ohms, respectively, and not in per unit. This usage was followed with the idea of keeping the change of variables under discussion, namely, the change from phase quantities to two-phase components, separate from any additional changes of variable, such as going to per-unit quantities or referring quantities on one side of a transformer to the other side.

Use of Transformers in the Equivalent Circuits. The equivalent circuits presented in this appendix consist of self-impedances and of ideal transformers having no leakage impedance nor exciting admittance. Such transformers offer no difficulty in computation; on the a-c calculating board they may be represented by actual transformers in which the leakage impedances and exciting admittances either are negligible or are compensated for by changes in other impedances of the circuit or by introducing adjustable sources of voltage. The transformer voltage ratios, generally one-to-one, are marked on the diagrams, and the polarity is understood to be subtractive; but a negative value of the ratio is equivalent to additive polarity. In one case the imaginary ratio $1{:}j$ is used. For a voltage ratio of $1{:}j$ the current ratio is also $1{:}j$; that is, both current and voltage are shifted 90 degrees in the same direction. (In general, the current ratio must be the conjugate of the reciprocal of the voltage ratio to make the complex power equal in the two windings.)

Simplification of Equivalent Circuits. In all the equivalent circuits the three substitute networks are shown as insulated from each other, constituting a six-wire circuit; and the lower or neutral side of each network is shown without impedance. It is permissible to combine the neutral sides of the three networks, thus forming a four-wire circuit. In some cases it is more convenient to join the neutral side of one network to the upper or line side of another. Such a case is the line-to-ground short circuit, figure 7*a*, in which the transformer may be eliminated if such a connection be made.

Wherever two networks or subnetworks are coupled through a single transformer, the transformer may be replaced by a conductive connection if voltages, currents, and impedances on one side be referred to the other side (no change if ratio is 1:1). If the networks are coupled through several transformers of the same ratio, one transformer may be replaced by a direct connection and the others by 1:1 transformers, or in some cases also by direct connections. If the networks are coupled through transformers of different ratios, one transformer may be replaced by a direct connection and the ratios of the others changed accordingly.

Another way in which the transformers may sometimes be eliminated can be illustrated by reference to figure 12. The 1:1 transformer in that figure may be omitted if impedance Z_{xy} be placed in the common neutral wire of networks x and y.

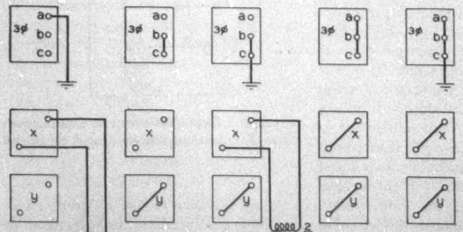
By elimination of transformers as suggested, the equivalent circuits may be considerably simplified. However, any such simplifications which would remove the insulation between the substitute networks have not been made in the circuits for three-phase circuit elements presented here because the best method of simplifying the equivalent circuit of any given three-phase network depends on what elements the complete network consists of.

Series Impedances

1. General Series Impedances With Nonreciprocal Mutual Impedances

The most general case of series impedances is the one in which the self-impedances of the three phases are unequal and in which there are mutual impedances between phases which are both unequal and nonreciprocal. (The mutual impedance between two circuits is nonreciprocal if the voltage produced in the first circuit by unit current in the second circuit is not equal to the voltage produced in the second circuit by unit current in the first.) Although this general case seldom occurs in practice, it is well to develop it first and then to derive various special cases of practical interest from it.

Let the impedances be designated by Z with two subscripts, the first of which refers to the voltage, the second to the current. The phase voltage drops may then be



(a) ag (b) bc (c) bcg (d) abc (e) abcg

Figure 7. Short circuits symmetrical with respect to phase a, and their equivalent circuits in two-phase co-ordinates

written as follows in terms of the phase currents and impedances:

$$\left.\begin{aligned}V_{la} - V_{ra} &= Z_{aa}I_a + Z_{ab}I_b + Z_{ac}I_c\\ V_{lb} - V_{rb} &= Z_{ba}I_a + Z_{bb}I_b + Z_{bc}I_c\\ V_{lc} - V_{rc} &= Z_{ca}I_a + Z_{cb}I_b + Z_{cc}I_c\end{aligned}\right\} \quad (1a)$$

The corresponding expressions in symmetrical components are:

$$\left.\begin{aligned}V_{l0} - V_{r0} &= Z_{00}I_0 + Z_{01}I_1 + Z_{02}I_2\\ V_{l1} - V_{r1} &= Z_{10}I_0 + Z_{11}I_1 + Z_{12}I_2\\ V_{l2} - V_{r2} &= Z_{20}I_0 + Z_{21}I_1 + Z_{22}I_2\end{aligned}\right\} \quad (1b)$$

where each Z is a certain function of the Z's in equations 1*a*.[9]

The corresponding expressions in two-phase components are:

$$\left.\begin{aligned}V_{lx} - V_{rx} &= Z_{xx}I_x + Z_{xy}I_y + Z_{xz}I_z\\ V_{ly} - V_{ry} &= Z_{yx}I_x + Z_{yy}I_y + Z_{yz}I_z\\ V_{lz} - V_{rz} &= Z_{zx}I_x + Z_{zy}I_y + Z_{zz}I_z\end{aligned}\right\} \quad (1c)$$

where

$$\left.\begin{aligned}Z_{xx} &= (2/3)Z_{aa} + (1/6)(Z_{bb} + Z_{cc} + Z_{bc} + Z_{cb}) - (1/3)(Z_{ca} + Z_{ac} + Z_{ab} + Z_{ba})\\ &= \tfrac{1}{2}(Z_{11} + Z_{12} + Z_{21} + Z_{22})\\ Z_{xy} &= 1/(2\sqrt{3})(Z_{bb} - Z_{cc} - Z_{bc} + Z_{cb} - 2Z_{ab} + 2Z_{ac})\\ &= \tfrac{1}{2}j(-Z_{11} + Z_{12} - Z_{21} + Z_{22})\\ Z_{xz} &= (1/3)(Z_{aa} + Z_{ab} + Z_{ac}) - (1/6)(Z_{bb} + Z_{cc} + Z_{bc} + Z_{ca} + Z_{cb} + Z_{ba})\\ &= \tfrac{1}{2}(Z_{10} + Z_{20})\\ Z_{yx} &= 1/(2\sqrt{3})(Z_{bb} - Z_{cc} + Z_{bc} - Z_{cb} + 2Z_{ca} - 2Z_{ba})\\ &= \tfrac{1}{2}j(Z_{11} + Z_{12} - Z_{21} - Z_{22})\\ Z_{yy} &= \tfrac{1}{2}(Z_{bb} + Z_{cc} - Z_{bc} - Z_{cb})\\ &= \tfrac{1}{2}(Z_{11} - Z_{12} - Z_{21} + Z_{22})\\ Z_{yz} &= 1/(2\sqrt{3})\ (-Z_{bb} + Z_{cc} - Z_{bc} + Z_{ca} + Z_{cb} - Z_{ba})\\ &= \tfrac{1}{2}j\ (Z_{10} - Z_{20})\\ Z_{zx} &= (1/3)(Z_{aa} + Z_{ca} + Z_{ba}) - (1/6)(Z_{bb} + Z_{cc} + Z_{bc} + Z_{ab} + Z_{cb} + Z_{ac})\\ &= \tfrac{1}{2}(Z_{01} + Z_{02})\\ Z_{zy} &= 1/(2\sqrt{3})(-Z_{bb} + Z_{cc} + Z_{bc} - Z_{ab} - Z_{cb} + Z_{ac})\\ &= \tfrac{1}{2}j\ (-Z_{01} + Z_{02})\\ Z_{zz} &= (1/6)(Z_{aa} + Z_{bb} + Z_{cc} + Z_{bc} + Z_{ca} + Z_{ab} + Z_{cb} + Z_{ac} + Z_{ba}) = \tfrac{1}{2}Z_{00}\end{aligned}\right\} \quad (1d)$$

No equivalent circuit is offered for this general case on account of the difficulty of representing the nonreciprocal mutual impedances between substitute networks.

2. BALANCED SERIES IMPEDANCES WITH BALANCED NONRECIPROCAL MUTUAL IMPEDANCES (AS IN THREE-PHASE ROTATING MACHINERY)

This is a special case of case 1, where

$$\left.\begin{aligned}Z_{aa} &= Z_{bb} = Z_{cc}\\ Z_{ab} &= Z_{bc} = Z_{ca}\\ Z_{ac} &= Z_{ba} = Z_{cb}\end{aligned}\right\} \quad (2a)$$

Equations 1*d* become

$$\left.\begin{aligned}Z_{xx} &= Z_{yy} = Z_{aa} - \tfrac{1}{2}(Z_{bc} + Z_{cb})\\ &= \tfrac{1}{2}(Z_{11} + Z_{22})\\ Z_{xy} &= -Z_{yx} = (\sqrt{3}/2)(-Z_{bc} + Z_{cb})\\ &= \tfrac{1}{2}j(-Z_{11} + Z_{22})\\ Z_{zz} &= \tfrac{1}{2}(Z_{aa} + Z_{bc} + Z_{cb}) = \tfrac{1}{2}Z_{00}\\ Z_{xz} &= Z_{yz} = Z_{zx} = Z_{zy} = 0\end{aligned}\right\} \quad (2b)$$

The z network is independent of the others, but there is a nonreciprocal coupling between the x and y networks. For an equivalent circuit use figure 2, putting $r_1 = j$, $r_1Z_{xy} = \tfrac{1}{2}(Z_{11} - Z_{22})$, $Z_{xz} = Z_{yz} = 0$, $H = J = Z_{22}$, and $K = \tfrac{1}{2}Z_{00}$, and omitting transformers r_2 and r_3.

3. UNBALANCED SERIES IMPEDANCES WITH RECIPROCAL MUTUAL IMPEDANCES

This is a special case of case 1, where

$$Z_{bc} = Z_{cb},\quad Z_{ac} = Z_{ca},\quad Z_{ab} = Z_{ba} \qquad (3a)$$

Equations 1*d* become:

$$\left.\begin{aligned}Z_{xx} &= (2/3)(Z_{aa} - Z_{ab} - Z_{ac}) + (1/3)Z_{bc} + (1/6)(Z_{bb} + Z_{cc})\\ &= Z_{11} + \tfrac{1}{2}(Z_{12} + Z_{21})\\ Z_{yy} &= \tfrac{1}{2}(Z_{bb} + Z_{cc}) - Z_{bc}\\ &= Z_{11} - \tfrac{1}{2}(Z_{12} + Z_{21})\\ Z_{zz} &= (1/3)(Z_{bc} + Z_{ab} + Z_{ac}) + (1/6)(Z_{aa} + Z_{bb} + Z_{cc})\\ &= \tfrac{1}{2}Z_{00}\\ Z_{xy} &= Z_{yx} = (1/\sqrt{3})(Z_{ac} - Z_{ab}) + 1/(2\sqrt{3})(Z_{bb} - Z_{cc})\\ &= \tfrac{1}{2}j(Z_{12} - Z_{21})\\ Z_{xz} &= Z_{zx} = (1/3)(Z_{aa} - Z_{bc}) + (1/6)(Z_{ab} + Z_{ac} - Z_{bb} - Z_{cc})\\ &= \tfrac{1}{2}(Z_{01} + Z_{02})\\ Z_{yz} &= Z_{zy} = 1/(2\sqrt{3})(Z_{cc} - Z_{bb} + Z_{ac} - Z_{ab}) = \tfrac{1}{2}j(Z_{02} - Z_{01})\end{aligned}\right\} \quad (3b)$$

There is reciprocal coupling between each pair of networks. An equivalent circuit is shown in figure 2. For simplicity the transformer ratios, r_1, r_2, and r_3, may be taken as unity, though in some cases a different ratio may be advisable.

4. SERIES IMPEDANCES AND RECIPROCAL MUTUAL IMPEDANCES SYMMETRICAL WITH RESPECT TO PHASE a

This is a special case of cases 1 and 3, where

$$Z_{bb} = Z_{cc},\quad Z_{bc} = Z_{cb},\quad Z_{ab} = Z_{ba} = Z_{ac} = Z_{ca} \qquad (4a)$$

Equations 1*d* become:

$$\left.\begin{aligned}Z_{xx} &= (2/3)Z_{aa} + (1/3)(Z_{bb} + Z_{bc}) - (4/3)Z_{ab}\\ Z_{yy} &= Z_{bb} - Z_{bc}\\ Z_{zz} &= (1/6)Z_{aa} + (1/3)(Z_{bb} + Z_{bc}) + (2/3)Z_{ab}\\ Z_{xz} &= Z_{zx} = (1/3)(Z_{aa} - Z_{bb} - Z_{bc} + Z_{ab})\\ Z_{xy} &= Z_{yx} = Z_{yz} = Z_{zy} = 0\end{aligned}\right\} \quad (4b)$$

Network y is independent of the others, while x and z are coupled. For an equivalent circuit use figure 2, omitting transformers r_1 and r_3.

5. BALANCED SERIES IMPEDANCES WITH BALANCED RECIPROCAL MUTUAL IMPEDANCES

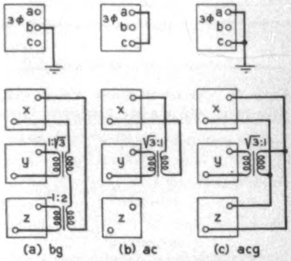
This is a special case of cases 1, 2, 3, and 4 where

$$\left.\begin{aligned}Z_{aa} &= Z_{bb} = Z_{cc} = Z_s\\ Z_{ab} &= Z_{bc} = Z_{ca} = Z_{ac} = Z_{ba}\\ &= Z_{cb} = Z_m\end{aligned}\right\} \quad (5a)$$

Equations 1*d* become:

$$\left.\begin{aligned}Z_{xx} &= Z_{yy} = Z_s - Z_m = Z_{11} = Z_{22}\\ Z_{zz} &= \tfrac{1}{2}Z_s + Z_m = \tfrac{1}{2}Z_{00}\\ Z_{xy} &= Z_{xz} = Z_{yx} = Z_{yz} = Z_{zx}\\ &= Z_{zy} = 0\end{aligned}\right\} \quad (5b)$$

The substitute networks are independent. For an equivalent circuit use figure 2, omitting all transformers and putting $Z_{xy} = Z_{xz} = Z_{yz} = 0$.



(a) bg (b) ac (c) acg

Figure 8. Short circuits symmetrical with respect to phase b, and their equivalent circuits in two-phase co-ordinates. For symmetry with respect to phase c, reverse network y

6. UNBALANCED SERIES IMPEDANCES WITHOUT MUTUAL IMPEDANCE

This is a special case of cases 1 and 3, where

$$Z_{bc} = Z_{cb} = Z_{ac} = Z_{ca} = Z_{ab} = Z_{ba} = 0 \qquad (6a)$$

Equations 1*d* become:

$$\left.\begin{aligned}Z_{xx} &= (2/3)Z_{aa} + (1/6)(Z_{bb} + Z_{cc})\\ Z_{yy} &= \tfrac{1}{2}(Z_{bb} + Z_{cc})\\ Z_{zz} &= (1/6)(Z_{aa} + Z_{bb} + Z_{cc})\\ Z_{xy} &= Z_{yx} = -Z_{yz} = -Z_{zy}\\ &= 1/(2\sqrt{3})(Z_{bb} - Z_{cc})\\ Z_{xz} &= Z_{zx}\\ &= (1/3)Z_{aa} - (1/6)(Z_{bb} + Z_{cc})\end{aligned}\right\} \quad (6b)$$

For an equivalent circuit use figure 2.

7. SERIES IMPEDANCE Z IN ONE WIRE (a)

Although this is a special case of case 6, we may as well start from the relations between phase quantities:

$$\left.\begin{aligned}V_{la} - V_{ra} &= I_aZ\\ V_{lb} - V_{rb} &= 0\\ V_{lc} - V_{rc} &= 0\end{aligned}\right\} \quad (7a)$$

The corresponding relations between two-phase components are:

$$\left.\begin{aligned}V_{lx} - V_{rx} &= 2(V_{lz} - V_{rz})\\ &= (2/3)\ Z(I_x + \tfrac{1}{2}I_z)\\ V_{ly} - V_{ry} &= 0\end{aligned}\right\} \quad (7b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $r_2 = 2$, $r_2Z_{xz} = (2/3)Z$, $Z_{xy} = Z_{yz} = 0$, and $H = J = K = 0$.

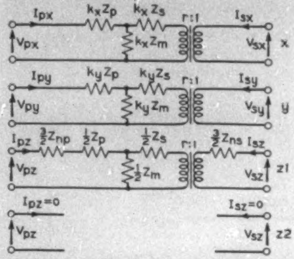


Figure 9. Equivalent circuits of wye-wye, delta-delta, and vee-vee transformer banks

For wye-wye, put $k_x = k_y = 1$, and use network z1

For delta-delta, put $k_x = k_y = 1/3$, and use network z2

For vee-vee, put $k_x = 1/3$, $k_y = 1$, and use network z2

The circuits shown are for zero phase displacement; for 180-degree displacement reverse the secondary terminals of each network

8. Equal Series Impedances Z in Two Wires (b and c)

Relations between phase quantities:

$$\left.\begin{aligned}V_{la} - V_{ra} &= 0\\ V_{lb} - V_{rb} &= ZI_b\\ V_{lc} - V_{rc} &= ZI_c\end{aligned}\right\} \quad (8a)$$

Relations between two-phase components:

$$\left.\begin{aligned}V_{lx} - V_{rx} &= -(V_{lz} - V_{rz})\\ &= (1/3)\,Z(I_x - I_z)\\ V_{ly} - V_{ry} &= ZI_y\end{aligned}\right\} \quad (8b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $r_2 = -1$, $r_2Z_{zz} = (1/3)Z$, $Z_{xy} = Z_{yz} = 0$, $H = K = 0$, and $J = Z$.

9. Equal Series Impedances in Two Wires (b and c) and a Different Impedance in the Third Wire (a)

Relations between phase quantities:

$$\left.\begin{aligned}V_{la} - V_{ra} &= Z_aI_a\\ V_{lb} - V_{rb} &= Z_bI_b\\ V_{lc} - V_{rc} &= Z_bI_c\end{aligned}\right\} \quad (9a)$$

Relations between two-phase components:

$$\left.\begin{aligned}V_{lx} - V_{rx} &= (1/3)(2Z_a + Z_b)I_x +\\ &\qquad (1/3)(Z_a - Z_b)I_z\\ V_{ly} - V_{ry} &= Z_bI_y\\ V_{lz} - V_{rz} &= (1/3)(Z_a - Z_b)I_x +\\ &\qquad (1/6)(Z_a + 2Z_b)I_z\end{aligned}\right\} \quad (9b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $Z_{xy} = Z_{yz} = 0$ and $J = Z_b$. If $Z_b > Z_a$, put $r_2 = -1$, $r_2Z_{zz} = (1/3)(Z_b - Z_a)$, $H = Z_a$, and $K = 1/2\,Z_a$. If $Z_b < Z_a$, put $r_2 = 2$, $r_2Z_{zz} = (2/3)(Z_a - Z_b)$, $H = Z_b$, and $K = 1/2\,Z_b$.

10. Equal Series Impedances Z_s in Two Wires (b and c) and Mutual Impedance Z_m Between Them

Relations between phase quantities:

$$\left.\begin{aligned}V_{la} - V_{ra} &= 0\\ V_{lb} - V_{rb} &= Z_sI_b + Z_mI_c\\ V_{lc} - V_{rc} &= Z_mI_b + Z_sI_c\end{aligned}\right\} \quad (10a)$$

Relations between two-phase components:

$$\left.\begin{aligned}V_{lx} - V_{rx} &= -(V_{lz} - V_{rz}) =\\ &\qquad (1/3)(Z_s + Z_m)(I_x - I_z)\\ V_{ly} - V_{ry} &= (Z_s - Z_m)I_y\end{aligned}\right\} \quad (10b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $r_2 = -1$, $r_2Z_{zz} = (1/3)(Z_s + Z_m)$, $Z_{xy} = Z_{yz} = 0$, $H = K = 0$, and $J = Z_s - Z_m$.

Open Circuits

11. Open Circuit in One Wire (a)

Relations between phase quantities:

$$\left.\begin{aligned}I_a &= 0\\ V_{lb} - V_{rb} &= 0\\ V_{lc} - V_{rc} &= 0\end{aligned}\right\} \quad (11a)$$

Corresponding relations between two-phase components:

$$\left.\begin{aligned}I_x + {}^1\!/_2I_z &= 0\\ V_{lx} - V_{rx} &= 2(V_{lz} - V_{rz})\\ V_{ly} - V_{ry} &= 0\end{aligned}\right\} \quad (11b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $r_2 = 2$, $Z_{zz} = \infty$, $Z_{xy} = Z_{yz} = 0$, and $H = J = K = 0$. The resulting circuit is like that portion of figure 10 between lines AA and BB, and consists of a coupling between the x and z networks through a 2:1 series transformer.

12. Open Circuit in Two Wires (b and c)

Relations between phase quantities:

$$\left.\begin{aligned}V_{la} - V_{ra} &= 0\\ I_b &= 0\\ I_c &= 0\end{aligned}\right\} \quad (12a)$$

Corresponding relations between two-phase components:

$$\left.\begin{aligned}(V_{lx} - V_{rx}) + (V_{lz} - V_{rz}) &= 0\\ I_x &= I_z\\ I_y &= 0\end{aligned}\right\} \quad (12b)$$

For an equivalent circuit use figure 2, omitting transformers r_1 and r_3, and putting $r_2 = -1$, $Z_{zz} = \infty$, $Z_{xy} = Z_{yz} = 0$, $H = K = 0$, and $J = \infty$ (that is, open network y).

13. Open Circuit in All Three Wires

Relations between phase quantities:

$$I_a = 0, \quad I_b = 0, \quad I_c = 0 \quad (13a)$$

Corresponding relations between two-phase components:

$$I_x = 0, \quad I_y = 0, \quad I_z = 0 \quad (13b)$$

This means that all three substitute networks are open at the point corresponding to the open circuit in the three-phase network.

Shunt Impedances

14. Wye-Connected Impedances With Neutral Grounded Through Impedance Z_n

This combination of impedances may be considered as two circuit elements in series, first, a group of series impedances, with or without mutual impedances, such as have been considered in cases 1 to 10 inclusive, and, second, the element shown in figure 3. The equivalent circuit will then consist of a series combination of the elements representing the two portions. The circuits for the first portion have already been given; that for the second portion (figure 3) will now be developed. The relations between phase quantities for this portion are:

$$V_a = V_b = V_c = Z_n(I_a + I_b + I_c) \quad (14a)$$

The corresponding relations between two-phase components are:

$$\left.\begin{aligned}V_x &= V_y = 0\\ V_z &= (3/2)Z_nI_z\end{aligned}\right\} \quad (14b)$$

The equivalent circuit, shown in figure 2*b*, consists of short circuits on the x and y networks and a shunt impedance $(3/2)Z_n$ in the z network. Z_n may have any value, from zero in case of solidly grounded neutral to infinity (open circuit) in case of isolated neutral. This equivalent circuit may be connected to the circuit of figure 2*a* as shown by the dotted lines.

15. Delta-Connected Impedances

Delta-connected impedances (figure 4*a*) may be considered as consisting of two circuit elements in cascade: first, a delta connection, and, second, series impedances. The equivalent circuit for the first element will be developed; that for the second element is shown in figure 2. The relations between line and delta quantities are as follows in terms of phase quantities. Let subscript l stand for line and d for delta, and let each delta phase be named from the opposite line phase:

$$\left.\begin{aligned}V_{da} &= V_{lb} - V_{lc}\\ V_{db} &= V_{lc} - V_{la}\\ V_{dc} &= V_{la} - V_{lb}\end{aligned}\right\} \quad (15a)$$

$$\left.\begin{aligned}I_{la} &= I_{dc} - I_{db}\\ I_{lb} &= I_{da} - I_{dc}\\ I_{lc} &= I_{db} - I_{da}\end{aligned}\right\} \quad (15b)$$

The corresponding relations in terms of two-phase components are:

$$\left.\begin{aligned}V_{dx} &= -\sqrt{3}V_{ly}\\ V_{dy} &= \sqrt{3}V_{lx}\\ V_{dz} &= 0\end{aligned}\right\} \quad (15c)$$

$$\left.\begin{aligned}I_{lx} &= \sqrt{3}I_{dy}\\ I_{ly} &= -\sqrt{3}I_{dx}\\ I_{lz} &= 0\end{aligned}\right\} \quad (15d)$$

Equations 15*c* and 15*d* are satisfied by the connections of the equivalent circuit in the left-hand part of figure 4*b*, to which may be connected on the right hand the equivalent circuit of figure 2.

If it is not desired to preserve the identity of the delta currents and voltages, the circuit can be reduced to a simpler form. The transformers of ratio $1 : \sqrt{3}$ may be omitted if all impedances in the right-hand part of the circuit are divided by 3. If there is no objection to a conductive connection between the neutral terminals of the x and y networks, the circuit can be reduced finally to three impedances connected in wye or delta. In the next case a delta equivalent circuit is derived directly.

16. DELTA-CONNECTED ADMITTANCES

Let the delta-connected admittances be Y_{ab}, Y_{bc}, and Y_{ca}. The relations between phase currents and voltages are:

$$\left.\begin{aligned} I_a &= (V_a - V_b)Y_{ab} - (V_c - V_a)Y_{ca} \\ I_b &= (V_b - V_c)Y_{bc} - (V_a - V_b)Y_{ab} \\ I_c &= (V_c - V_a)Y_{ca} - (V_b - V_c)Y_{bc} \end{aligned}\right\} \quad (16a)$$

The corresponding relations between two-phase components are:

$$\left.\begin{aligned} I_x &= (3/2)(Y_{ca} + Y_{ab})V_x + \\ &\qquad (\sqrt{3}/2)\,(Y_{ab} - Y_{ca})V_y \\ I_y &= (\sqrt{3}/2)(Y_{ab} - Y_{ca})V_x + \\ &\qquad (2Y_{bc} + {}^1/_2Y_{ca} + {}^1/_2Y_{ab})V_y \\ I_z &= 0 \end{aligned}\right\} \quad (16b)$$

An equivalent circuit is given in figure 5. A, B, and C are admittances whose values are:

$$\left.\begin{aligned} A &= Y_{ab}\,(3 - \sqrt{3}r)/2 + \\ &\qquad Y_{ca}\,(3 + \sqrt{3}r)/2 \\ B &= 2Y_{bc} + Y_{ab}(1 - \sqrt{3}/r)/2 + \\ &\qquad Y_{ca}(1 + \sqrt{3}/r)/2 \\ C &= (\sqrt{3}/2r)(Y_{ab} - Y_{ca}) \end{aligned}\right\} \quad (16c)$$

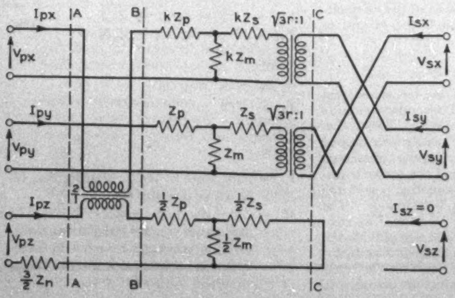
If $Y_{ab} > Y_{ca}$, put $r = 1$; if $Y_{ab} < Y_{ca}$, put $r = -1$.

Note that for symmetry with respect to phase a, $Y_{ab} = Y_{ca}$, and $C = 0$ (open circuit), which makes the x and y networks independent.

The results of this case may be applied to impedances connected in Y with isolated neutral, by first changing the Y to an equivalent delta.

Figure 10. Equivalent circuit for wye-delta or for open wye-open delta (reversed vee-vee) transformer bank

For wye-delta omit portion between AA and BB, and put $k = 1$. For open wye-open delta omit that portion of network z between BB and CC, and put $k = 3$. Connections shown are for positive-sequence voltages on delta side 90 degrees behind those on wye side



17. SINGLE IMPEDANCE Z CONNECTED LINE TO LINE

Relations between phase quantities:

$$I_a = 0, \quad I_b + I_c = 0, \quad V_b - V_c = ZI_b \qquad (17a)$$

Corresponding relations between two-phase components:

$$I_x = 0, \quad I_z = 0, \quad V_y = {}^1/_2ZI_y \qquad (17b)$$

The equivalent circuit consists of impedance $Z/2$ in shunt with network y.

18. SINGLE IMPEDANCE Z CONNECTED LINE TO NEUTRAL

Relations between phase quantities:

$$V_a = ZI_a, \quad I_b = 0, \quad I_c = 0 \qquad (18a)$$

Corresponding relations between two-phase components:

$$V_x + V_z = (3/2)ZI_x, \quad I_x = I_z, \quad I_y = 0 \qquad (18b)$$

An equivalent circuit is shown in figure 6.

Short Circuits Symmetrical With Respect to Phase a

19. LINE-TO-GROUND SHORT CIRCUIT ON PHASE a

Relations between phase quantities:

$$V_a = 0, \quad I_b = 0, \quad I_c = 0 \qquad (19a)$$

Corresponding relations between two-phase components:

$$V_x + V_z = 0, \quad I_x = I_z, \quad I_y = 0 \qquad (19b)$$

Equivalent circuit, figure 7*a*.

20. LINE-TO-LINE SHORT CIRCUIT ON PHASES b AND c

Relations between phase quantities:

$$I_a = 0, \quad I_b + I_c = 0, \quad V_b = V_c \qquad (20a)$$

Corresponding relations between two-phase components:

$$I_z = 0, \quad I_x = 0, \quad V_y = 0 \qquad (20b)$$

Equivalent circuit, figure 7*b*.

21. TWO-LINE-TO-GROUND SHORT CIRCUIT ON PHASES b AND c

Relations between phase quantities:

$$I_a = 0, \quad V_b = 0, \quad V_c = 0 \qquad (21a)$$

Corresponding relations between two-phase components:

$$I_x + {}^1/_2I_z = 0, \quad V_x = 2V_z, \quad V_y = 0 \qquad (21b)$$

Equivalent circuit, figure 7*c*.

22. THREE-PHASE SHORT CIRCUIT NOT INVOLVING GROUND

Relations between phase quantities:

$$I_a + I_b + I_c = 0, \quad V_a = V_b = V_c \qquad (22a)$$

Corresponding relations between two-phase components:

$$I_z = 0, \quad V_x = 0, \quad V_y = 0 \qquad (22b)$$

Equivalent circuit, figure 7*d*.

23. THREE-PHASE SHORT CIRCUIT INVOLVING GROUND

Relations between phase quantities:

$$V_a = V_b = V_c = 0 \qquad (23a)$$

Corresponding relations between two-phase components:

$$V_x = V_y = V_z = 0 \qquad (23b)$$

Equivalent circuit, figure 7*e*.

Short Circuits Not Symmetrical With Respect to Phase a

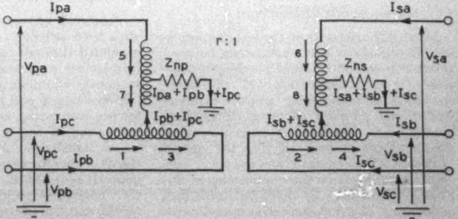
These are included to show that two-phase components can be used in problems of simultaneous faults. Only faults symmetrical with respect to phase b are treated in detail. For faults symmetrical with respect to phase c, the equations in two-phase components differ only in changed algebraic sign of I_y and V_y; the equivalent circuits differ only in reversed polarity of the y network.

24. LINE-TO-GROUND SHORT CIRCUIT ON PHASE b

Relations between phase quantities:

$$I_a = 0, \quad I_c = 0, \quad V_b = 0 \qquad (24a)$$

Figure 11. Tee-tee transformer bank with grounded neutrals on both windings



Corresponding relations between two-phase components:

$$\left.\begin{aligned} I_x = I_y/\sqrt{3} = -{}^1/_2 I_z \\ V_x + \sqrt{3}V_y - 2V_z = 0 \end{aligned}\right\} \quad (24b)$$

Equivalent circuit, figure 8*a*.

25. Line-to-Line
Short Circuit on Phases a and c

Relations between phase quantities:

$$I_b = 0, \quad I_a + I_c = 0, \quad V_a = V_c \qquad (25a)$$

Corresponding relations between two-phase components:

$$I_z = 0, \quad I_x + \sqrt{3}I_y = 0, \quad V_x = V_y/\sqrt{3} \qquad (25b)$$

Equivalent circuit, figure 8*b*.

26. Two-Line-to-Ground Short Circuit on Phases a and c

Relations between phase quantities:

$$I_b = 0, \quad V_c = 0, \quad V_a = 0 \qquad (26a)$$

Corresponding relations between two-phase components:

$$\left.\begin{aligned} I_x + \sqrt{3}I_y - I_z = 0 \\ V_x = V_y/\sqrt{3} = -V_z \end{aligned}\right\} \quad (26b)$$

Equivalent circuit, figure 8*c*.

Transformer Banks

27. Wye-Wye Connection

Each transformer, all three of which are assumed to be identical, is represented by an equivalent *T* circuit in cascade with an ideal transformer of the same ratio (r:1) as that of the actual transformer. The *T* circuit consists of the following impedances, all referred to the primary side: Z_p, the primary leakage impedance, Z_s, the secondary leakage impedance, and Z_m, the exciting impedance. Since the three transformers constitute a balanced circuit, their representation in the substitute networks is the same as the representation of a single transformer, except that in the *z* network the impedances have one-half their true values. The neutral impedances, Z_{np} and Z_{ns}, appear in the *z* network multiplied by 3/2, just as in case 14 (wye-connected impedances). The complete equivalent circuit for the bank and neutral resistors is given in figure 9 with $k_x = k_y = 1$ and the *z* network like that marked "*z*1." The ideal transformers, marked "r:1," may be omitted if secondary currents and voltages are referred to the primary side, and in many cases the shunt branches Z_m may be omitted also; then the equivalent circuit consists simply of a series impedance in each substitute network.

28. Delta-Delta Connection

Most of the remarks on the last case apply to this one also. The circuit may be considered to consist of three portions in cascade: (1) delta connection, (2) transformers, (3) delta connection; and the equivalent circuit consists of three corresponding portions. The two portions representing the delta connections are like the circuit of figure 4*b*, developed in case 15. The circuit resulting from the combination of the three portions may be simplified, with loss of identity of the delta currents and voltages, by replacing the 1:$\sqrt{3}$ transformers of figure 4 by direct connections and dividing the transformer impedances, expressed in ohms, by 3. (If expressed in per unit, they are not changed.) The equivalent circuit is then that of figure 9 with $k_x = k_y = 1/3$, and with the *z* network like that marked "*z*2."

29. Wye-Delta Connection

The equivalent circuit (figure 10) is built up of portions similar to those found in the last two cases. It is worthy of note that the *x* network on the primary side is connected to the *y* network on the secondary side, and the *y* network on the primary side is connected to the *x* network on the secondary side. Furthermore, a reversal of polarity occurs in one of the two connections (shown in the *py-sx* connection for transformer connections giving voltages of the delta side 90 degrees behind the voltages of the wye side).

30. Open Delta or Vee-Vee Connection

The open delta transformer bank may be considered to consist of the following portions in cascade: (1) delta connection, (2) open circuit in phase *a*, (3) transformers, (4) open circuit in phase *a*, and (5) delta connection. The equivalent circuit may be built up from corresponding portions, using figure 4 for the delta connections and that portion of figure 10 between lines *AA* and *BB* for the open circuits. The resulting circuit is then simplified to the circuit of figure 9 by two steps: (1) eliminate the 2:1 transformers representing the open circuits by multiplying the transformer impedances in the *z* network by 4 and adding them to the corresponding *x* impedances; (2) replace the $\sqrt{3}$:1 transformers by direct connections and divide the transformer impedances by 3. The equivalent circuit then becomes that of figure 9 with $k_x = 1/3$ and $k_y = 1$. Note that the effect of removing one transformer from a delta-delta bank is to increase the *y* impedances threefold.

31. Open Wye-Open Delta or Reversed Vee-Vee Connection

The equivalent circuit for this case (figure 10) may be derived from that for a wye-delta bank, just as that for an open delta bank was derived from that for a delta-delta bank, by inserting an open circuit in phase *a* on each side of the transformers. The effect of thus removing one transformer is to increase the impedance of the *px-sy* circuit threefold and to couple the *px* and *pz* networks.

32. Tee-Tee Connection

Figure 11 shows the tee-tee connection with both primary and secondary circuits grounded through impedance. Two transformers are used, each having two tapped windings—the main transformer, connected between lines *b* and *c*, and the teaser transformer, connected between line *a* and the center tap of the main transformer. The teaser transformer may be tapped at two-thirds of the turns from line *a* to provide the neutral connections. In the following analysis, however, exciting current is neglected, and the transformers are assumed to be ungrounded. The main transformer must be treated as a four-circuit transformer to find the impedance drops. Let the portions of the windings be numbered from 1 to 4 as shown in figure 11, the odd numbers being assigned to the primary and the even numbers to the secondary side. The impedance drop between any two windings, *i* and *j*, of an *n*-circuit transformer, neglecting exciting current, is given by

$$V_i - V_j = -{}^1/_2 \sum_{k=1}^{n} (Z_{ik} - Z_{jk}) I_k \qquad (32a)$$

where V_i and V_j are the terminal voltages of windings *i* and *j*, respectively, I_k the current in winding *k*, Z_{ik} the short-circuit or equivalent impedance of windings *i* and *k*, etc., all quantities being referred to the same winding. $Z_{ii} = Z_{jj} = 0$. Applying formula 32*a* to the main transformer, assuming for convenience that the two center taps are at the same potential, and not referring all quantities to the same side, one obtains:

$$V_{pb} - rV_{sb} = -{}^1/_2[-Z_{12}I_{pb} + Z_{12}I_{sb}/r + (Z_{13} - Z_{32})(-I_{pc}) + (Z_{14} - r^2Z_{24})(-I_{sc}/r)] \qquad (32b)$$

$$V_{pc} - rV_{sc} = -{}^1/_2[-Z_{34}I_{pc} + Z_{34}I_{sc}/r + (Z_{13} - Z_{14})(-I_{pb}) + (Z_{32} - r^2Z_{24})(-I_{sb}/r)] \qquad (32c)$$

Regarding the teaser transformer as a two-circuit transformer of impedance *T* (referred to primary),

$$V_{pa} - rV_{sa} = TI_{pa} \qquad (32d)$$

The following current equations are obtained by summing the ampere-turns on each core:

$$rI_{pb} + I_{sb} - rI_{pc} - I_{sc} = 0 \qquad (32e)$$

$$rI_{pa} + I_{sa} = 0 \qquad (32f)$$

and the following are obtained from Kirchhoff's current law:

$$I_{pa} + I_{pb} + I_{pc} = 0 \qquad (32g)$$

$$I_{sa} + I_{sb} + I_{sc} = 0 \qquad (32h)$$

The following equations in two-phase components are equivalent to equations 32*b* to 32*h* in phase quantities:

$$\left.\begin{aligned} rI_{px} + I_{sx} = 0 \\ rI_{py} + I_{sy} = 0 \end{aligned}\right\} \quad (32i)$$

$$\left.\begin{aligned} I_{pz} = 0 \\ I_{sz} = 0 \end{aligned}\right\} \quad (32j)$$

$$\left.\begin{aligned} V_{px} - rV_{sx} = Z_xI_{px} + Z_{xy}I_{py} \\ V_{py} - rV_{sy} = Z_{xy}I_{px} + Z_yI_{py} \end{aligned}\right\} \quad (32k)$$

where

$Z_x = 2T/3 + M'/6$
$Z_y = M/2$
$Z_{xy} = (Z_{12} - Z_{34})/2\sqrt{3}$

where

T = impedance of teaser transformer, referred to primary side
$M = Z_{12} + Z_{34} + Z_{32} + Z_{14} - Z_{13} - r^2Z_{24}$
= impedance of main transformer measured on windings 1 and 3 in series with windings 2 and 4 in series short-circuited

$M' = Z_{12} + Z_{34} + Z_{13} + r^2Z_{24} - Z_{32} - Z_{14}$
= impedance of main transformer measured on winding 1 in series with 3 reversed, when winding 2 in series with winding 4 reversed is short-circuited

An equivalent circuit is given in figure 12. Note that with symmetrical construction of the main transformer, $Z_{xy} = 0$, resulting in simplification of the equivalent circuit.

If both neutrals are grounded, z current can flow to ground freely from either side. All four circuits (x, y, pz, and sz) are coupled together through different mutual impedances, making the equivalent circuit very complicated.

33. Scott Connection

The discussion is limited to the case of isolated neutrals. Let the currents and voltages on the two-phase (secondary) side be denoted by subscripts sx and sy; no substitutions need be made for them. Let the ratios of the main and teaser transformers be denoted by r_m and r_t, respectively; ordinarily $r_t = (\sqrt{3}/2)r_m$. Let the windings of the main transformer be denoted as follows: 1 and 2, the halves of the primary winding connected to lines c and b, respectively; 3, the secondary winding. Exciting current is neglected.

The equations in phase currents and voltages are:

$$\left.\begin{aligned}
&I_{pa} + I_{pb} + I_{pc} = 0\\
&r_tI_{pa} + I_{sx} = 0\\
&r_m(I_{pc} - I_{pb}) + 2I_{sy} = 0\\
&V_{pa} - r_tV_{sx} = TI_{pa}\\
&V_{pb} + V_{pc} = -{}^1/_2[-Z_{12}(I_{pb}+I_{pc}) +\\
&\qquad (Z_{13} - Z_{23})I_{sy}\,2/r_m]\\
&(V_{pc} - V_{pb}) - r_mV_{sy} = -{}^1/_2\times\\
&\quad [(Z_{12} - 2Z_{13})I_{pc} + (Z_{12} - 2Z_{23})\times\\
&\qquad (-I_{pb}) + (Z_{13} + Z_{23})I_{sy}\,2/r_m]
\end{aligned}\right\} \quad \textbf{(33a)}$$

The last two equations are obtained from 32*a*.

The corresponding equations in two-phase components are:

$$\left.\begin{aligned}
&I_{pz} = 0\\
&r_tI_{px} + I_{sx} = 0\\
&(\sqrt{3}/2)r_mI_{py} + I_{sy} = 0\\
&V_{px} - (2/3)r_tV_{sx} = Z_xI_{px} + Z_{xy}I_{py}\\
&V_{py} - (r_m/\sqrt{3})V_{sy} = Z_{xy}I_{px} + Z_yI_{py}
\end{aligned}\right\} \quad \textbf{(33b)}$$

where

$$\left.\begin{aligned}
Z_x &= 2T/3 + Z_{12}/6\\
Z_y &= M/2\\
Z_{xy} &= (Z_{23} - Z_{13})/2\sqrt{3}
\end{aligned}\right\} \quad \textbf{(33c)}$$

M = short-circuit impedance of main transformer measured from primary side (that is, measured on windings 1 and 2 in series with winding 3 short-circuited), ohms

T = short-circuit impedance of teaser transformer measured from primary side

Z_{23} = impedance measured on winding 2 with winding 3 short-circuited, ohms; etc.

An equivalent circuit is given in figure 12. Note that the secondary terminal voltages in this circuit are equal to two-thirds the actual secondary voltages. This is explainable by reference to equation 13 for power in terms of two-phase components.

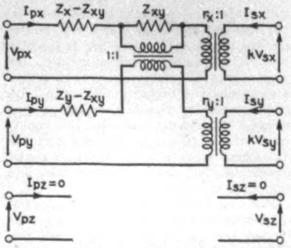


Figure 12. Equivalent circuit of ungrounded tee-tee or Scott transformer bank, exciting current neglected

For tee-tee, put $k = 1$, $r_x = r_y = r$. For Scott, put $k = 2/3$, $r_x = r_t$, $r_y = 0.866\, r_m$

Untransposed Lines

34. Line Without Ground Wires

Let

R_a, R_b, R_c = resistances of wires a, b, c per unit length, ohms per meter

D_{aa}, D_{bb}, D_{cc} = geometric mean radii of wires a, b, c (0.779 times actual radius for a round wire)

D_{ab}, D_{bc}, D_{ca} = geometric mean distances between wires (center-to-center distances for round wires). The D's may be in any units provided that all are in the same units

$\lambda_a, \lambda_b, \lambda_c$ = magnetic flux linkages per unit length of wires a, b, c, webers per meter

μ_0 = permeability of air = 10^{-7} henry per meter (unrationalized meter-kilogram-second units)

f = frequency, cycles per second

$\omega = 2\pi f$

V = voltage rise per unit length along line, volts per meter

I = line current, amperes

Z = impedance per unit length of line, ohms per meter

Subscripts a, b, c, x, y, z are used with V, I, and Z as heretofore

ρ = earth resistivity, ohm-meters

The relations between phase currents and voltages which hold if $I_z = 0$ are:

$$\left.\begin{aligned}
V_a &= R_aI_a + j\omega\lambda_a\\
V_b &= R_bI_b + j\omega\lambda_b\\
V_c &= R_cI_c + j\omega\lambda_c
\end{aligned}\right\} \quad \textbf{(34a)}$$

where

$$\left.\begin{aligned}
\lambda_a &= -2\mu_0\,(I_a \log_e D_{aa} +\\
&\qquad I_b \log_e D_{ab} + I_c \log_e D_{ac})\\
\lambda_b &= -2\mu_0\,(I_a \log_e D_{ab} +\\
&\qquad I_b \log_e D_{bb} + I_c \log_e D_{bc})\\
\lambda_c &= -2\mu_0\,(I_a \log_e D_{ac} +\\
&\qquad I_b \log_e D_{bc} + I_c \log_e D_{cc})
\end{aligned}\right\} \quad \textbf{(34b)}$$

Now assume current component I_x to flow alone, that is, assume

$$I_a = I_x, \quad I_b = I_c = -{}^1/_2I_x \qquad \textbf{(34c)}$$

Substitute equations 34*b* into 34*a*, 34*c* into the resulting equations, and the latter into equations 2. The division of the resulting expressions for V_x, V_y, and V_z by I_x gives Z_{xx}, Z_{xy}, and Z_{xz}, respectively. Next assume current component I_y to flow alone, that is, assume

$$I_a = 0, \quad I_c = -I_b = (\sqrt{3}/2)I_y \qquad \textbf{(34d)}$$

and by a similar procedure obtain Z_{yy} and Z_{yz}. This leaves only Z_{zz}, which may be found from the knowledge that it is one-half the zero-sequence impedance, Z_{00}. The impedances thus found are:

$$\left.\begin{aligned}
Z_{xx} &= (2/3)R_a + (1/6)(R_b + R_c) +\\
&\quad j\omega(1/3)\mu_0 \log_e \frac{D_{ab}{}^4D_{ac}{}^4}{D_{aa}{}^4\,D_{bb}D_{cc}D_{bc}{}^2}\\
Z_{xy} &= (1/2\sqrt{3})(R_b - R_c) +\\
&\quad j\omega\,(1/\sqrt{3})\mu_0 \times\\
&\qquad \log_e (D_{ab}{}^2D_{cc}/D_{ac}{}^2D_{bb})\\
Z_{xz} &= (1/3)R_a - (1/6)(R_b + R_c) +\\
&\quad j\omega(1/3)\mu_0 \times\\
&\qquad \log_e(D_{bb}D_{cc}D_{bc}{}^2/D_{aa}{}^2D_{ab}D_{ac})\\
Z_{yy} &= {}^1/_2(R_b + R_c) +\\
&\qquad j\omega\mu_0 \log_e (D_{bc}{}^2/D_{bb}D_{cc})\\
Z_{yz} &= (1/2\sqrt{3})(R_c - R_b) +\\
&\quad j\omega\,(1/\sqrt{3})\mu_0 \times\\
&\qquad \log_e (D_{ab}D_{bb}/D_{ac}D_{cc})\\
Z_{zz} &= (1/6)(R_a + R_b + R_c) +\\
&\quad (3/2)R_g + j\omega 3\mu_0 \log_e (H/A)
\end{aligned}\right\} \quad \textbf{(34e)}$$

where

$R_g = 0.99 \times 10^{-6}f$ ohms per meter
$H = 2{,}160\,\sqrt{\rho/f}$ feet
$A = (D_{aa}D_{bb}D_{cc}D_{ab}{}^2D_{bc}{}^2D_{ac}{}^2)^{1/9}$ feet

The impedances of equations 34*e* may be used in equations 1*c* and in the equivalent circuit of figure 2. Note that if the line is symmetrical with respect to wire a, that is, if spacing $D_{ab} = D_{ac}$ and if wires b and c are alike ($R_b = R_c$ and $D_{bb} = D_{cc}$), then $Z_{xy} = 0$ and $Z_{yz} = 0$, making the y network independent.

35. Symmetrical Line With Two Ground Wires

The discussion is confined to the case in which both the line wires and the ground wires are symmetrical with respect to a plane through wire a. With such a configuration, both I_x and I_z, especially the latter, induce in the ground wires currents which are equal in the two wires and which return in the ground. I_y, on the other hand, induces a circulating current in the ground wires. The currents in the ground wires can be computed by established methods, after which the impedances can be calculated in the same general way as in the last case.

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Discussion

A. Boyajian (General Electric Company, Pittsfield, Mass.): I wish to make some comments as to title, method of derivation, and final results.

TITLE

The co-ordinates discussed by Professor Kimbark are not true two-phase quantities, and there is only one logical name for them: Clarke co-ordinates or Clarke components. Certain types of co-ordinates are called Cartesian co-ordinates after Descartes who first formulated them. I frequently call symmetrical co-ordinates, Fortescue co-ordinates. The system discussed by Professor Kimbark may have been used in some fragmentary form by others, but Miss Edith Clarke being the first person to systematize it, it is fitting that we name the system after her—Clarke co-ordinates.

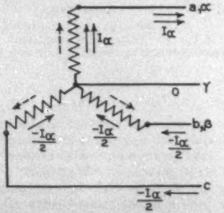

Figure 1. Illustrating the flow of I_α

Solid arrows represent the actual currents; dotted arrows the positive directions of the three-phase system

$$i_a' = I_\alpha$$
$$i_b' = -I_\alpha/2$$
$$i_c' = -I_\alpha/2$$

DERIVATION AND RESULTS

A transformation which replaces a given system of circuits by another, presumably more convenient, equivalent system of circuits, should be subjected to two tests: (*a*) physical interpretation, and (*b*) mathematical consistency. The first is essential because engineers are visual-minded, and they cannot use a system unless they have a clear physical understanding of it. We must be able to visualize the current and voltage components and also the impedances of the system to the new currents. The second is essential not merely to assure correctness, but also for the perfection and simplification of the technique.

Professor Kimbark has given some physical interpretations, but they have not been carried through to the voltages and impedances, so that neither he nor the average reader is likely to be aware of lack of fit at some points of the structure. The voltage transformation equations must have been obtained either by trial and error or by intuition, because they are not the inverse of the current transformation equations; and, as a consequence, his power equation 13 has to have an arbitrary correction factor of 3/2 applied to it.

Mathematical consistency demands for instance, that, while the transformation of the currents may be assumed arbitrarily, this having been done, the transformation of the voltages may not be assumed arbitrarily, but has to be the tensorial inverse of the first, for which we have a standardized routine.

I wish to develop the Clarke transformation for a triple purpose: (*a*) to obtain a consistent system, (*b*) to show clearly its physical significance, and (*c*) to utilize the present case to illustrate a typical procedure in developing any equivalent system and the many benefits of such procedure. I shall use Miss Clarke's notation: Greek letters for the new quantities, English letters for the customary three-phase quantities.

I_α

Figure 1 of this discussion illustrates positive I_α: as pointed out both by Miss Clarke and Professor Kimbark, this is a current which flows in phase *a* and returns equally through the other two. The algebraic signs are determined by assuming the positive directions in the three-phase system as from neutral outward. Thus, a positive I_α produces a positive component of current (i_a') in phase *a*, and negative half currents in the other two phases:

$$i_a' = I_\alpha, \quad i_b' = -I_\alpha/2, \quad i_c' = -I_\alpha/2 \quad (1)$$

Figure 1 defines also the impedance of the system to I_α.

I_β

Figure 2 illustrates a positive I_β: it is a current flowing between phases *b* and *c* only, in the positive sense of phase *b*. The three-phase currents corresponding to I_β are

$$i_a'' = 0, \quad i_b'' = I_\beta, \quad i_c'' = -I_\beta \quad (2)$$

Figure 2 defines also the impedance of the system to I_β.

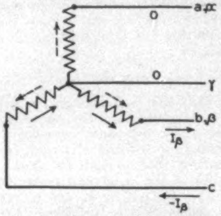

Figure 2. Illustrating the flow of I_β

Solid arrows represent the actual currents; dotted arrows the positive directions of the three-phase system

$$i_a'' = 0$$
$$i_b'' = I_\beta$$
$$i_c'' = -I_\beta$$

I_γ

Figure 3 illustrates a positive I_γ: it is the current in the neutral and provides equal positive currents of one-third value in all three lines. Thus, the three-phase currents corresponding to I_γ are

$$i_a''' = I_\gamma/3, \quad i_b''' = I_\gamma/3, \quad i_c''' = I_\gamma/3 \quad (3)$$

Table I. Transformation Matrices

		For Currents				For Voltages		
	$\mu \backslash m$				$\mu \backslash m$			
Clarke	$A_m^\mu =$	2/3	−1/3	−1/3	$A_\mu^m =$	2/3	−1/3	−1/3
		0	$\frac{1}{\sqrt{3}}$	$\frac{-1}{\sqrt{3}}$		0	$\frac{1}{\sqrt{3}}$	$\frac{-1}{\sqrt{3}}$
		1/3	1/3	1/3		1/3	1/3	1/3
	$\mu \backslash m$				$\mu \backslash m$			
Kimbark	$A_m^\mu =$	2/3	−1/3	−1/3	$A_\mu^m =$	2/3	−1/3	−1/3
		0	$\frac{-1}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$		0	$\frac{-1}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$
		2/3	2/3	2/3		1/3	1/3	1/3
	$\mu \backslash m$				$\mu \backslash m$			
Boyajian	$A_m^\mu =$	2/3	−1/3	−1/3	$A_\mu^m =$	1	−1/2	−1/2
		0	1/2	−1/2		0	1	−1
		1	1	1		1/3	1/3	1/3

Figure 3 defines also the impedance of the system for I_γ.

Attention may be called to the fact that I_γ is the current in the *neutral;* and, therefore, the neutral wire is one of the circuits of the new equivalent system, not of the old three-phase system. In the three-phase system, the neutral lead is merely a return wire, not an independent circuit. To emphasize this point, let us note that each system has three independent circuits: the circuits of the three-phase system are *a*, *b*, *c;* while those of the equivalent Clarke system are α, β, γ. The terminals *a* and α coincide, *b* and β coincide, but *c* and γ are separate. Terminal *c* represents an independent circuit of the three-phase system, but only a return conductor of the Clarke system (of circuit β). It will be seen also that I_γ is not strictly the old zero-sequence current but one equal to three times the old zero-sequence current. If we were to define our I_γ as Fortescue's I_0, we would lose the identity—the nice physical picture—of circuit γ, besides having to define V_γ as $3V_0$ and thereby losing also the nice physical picture of V_γ.

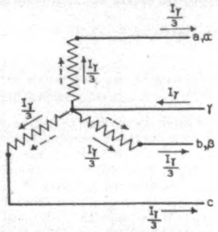

Figure 3. Illustrating the flow of I_γ

Solid arrows represent the actual currents; dotted arrows the positive directions of the three-phase system

$$i_a''' = I_\gamma/3$$
$$i_b''' = I_\gamma/3$$
$$i_c''' = I_\gamma/3$$

RELATIONSHIP OF RESULTANT CURRENTS

The total three-phase current, I_a, in phase *a* is of course the sum of all three of its Clarke components, i_a', i_a'', and i_a''', from equations 1, 2, and 3. The same comment applies to I_a and I_c; hence,

$$\left.\begin{aligned} I_a &= I_\alpha + 0I_\beta + (1/3)I_\gamma \\ I_b &= (-1/2)I_\alpha + I_\beta + (1/3)I_\gamma \\ I_c &= (-1/2)I_\alpha - I_\beta + (1/3)I_\gamma \end{aligned}\right\} \quad (4)$$

The matrix of the transformation from Clarke co-ordinates to three-phase co-ordinates may be copied from the coefficients of (4), and may be designated (in tensor notation) as $A_\mu{}^m$:

$$A_\mu{}^m = \begin{array}{c|c|c|c} m \diagdown \mu & \alpha & \beta & \gamma \\ \hline a & 1 & 0 & 1/3 \\ \hline b & -1/2 & 1 & 1/3 \\ \hline c & -1/2 & -1 & 1/3 \end{array} \quad (5a)$$

CLARKE VOLTAGES IN TERMS OF THREE-PHASE VOLTAGES

Equations 1, 2, and 3 are arbitrary; but once they are accepted, every bit of the rest of the work will follow as a mathematical necessity. Those who are familiar with the tensor point of view, know that equation 4, hence matrix (5*a*) transposed, (that is, rows and columns interchanged)

$$A_\mu{}^m = \begin{array}{c|c|c|c} \mu \diagdown m & a & b & c \\ \hline \alpha & 1 & -1/2 & -1/2 \\ \hline \beta & 0 & 1 & -1 \\ \hline \gamma & 1/3 & 1/3 & 1/3 \end{array} \quad (5b)$$

defines the inverse transformation of the voltages, that is, from the three-phase system to the Clarke system; and thus we may write, out of mathematical necessity and hence with entire confidence,

$$\left.\begin{aligned} V_\alpha &= V_a - (1/2)V_b - (1/2)V_c \\ V_\beta &= 0 + V_b - V_c \\ V_\gamma &= (1/3)V_a + (1/3)V_b + (1/3)V_c \end{aligned}\right\} \quad (6)$$

PHYSICAL INTERPRETATION OF CLARKE VOLTAGES

The new voltage components, as defined by equation 6, are shown in figure 4.

V_β is simply the line voltage between *b* and *c*.

V_α is the three-phase system voltage parallel to I_α, that is, the vector from the vertex *a* to the midpoint of the line voltage *b-c*.

Finally, V_γ is what we have always known as the neutral shift, or, the zero-sequence voltage.

CLARKE CO-ORDINATES OF CURRENTS IN TERMS OF THREE-PHASE CO-ORDINATES OF CURRENTS

Equation 4 gave us the three-phase currents in terms of the Clarke currents; so, if we wish to obtain the Clarke currents in terms of the three-phase currents, we invert* matrix 5*b*, and obtain

$$A_\mu{}^m = \begin{array}{c|c|c|c} \mu \diagdown m & a & b & c \\ \hline \alpha & 2/3 & -1/3 & -1/3 \\ \hline \beta & 0 & 1/2 & -1/2 \\ \hline \gamma & 1 & 1 & 1 \end{array} \quad (7)$$

Matrix 7 means that the new current equations will be

$$\left.\begin{aligned} I_\alpha &= (2/3)I_a - (1/3)I_b - (1/3)I_c \\ I_\beta &= 0 + (1/2)I_b - (1/2)I_c \\ I_\gamma &= I_a + I_b + I_c \end{aligned}\right\} \quad (8)$$

COMPARISON OF RESULTS

The transformation matrices used by Miss Clarke, Professor Kimbark, and the writer are exhibited in table I of this discussion for easy comparison.

Some differences are to be seen easily. That however does not mean that one or another of these matrices must be wrong, but rather that in one or another the equivalence is not *complete*, even though, undoubtedly, the various applications that have been made are all valid.

The Clarke matrices have the distinction of being identical for currents and voltages. This is secured, however, at the expense of the vector power equation, because the current and voltage transformation matrices are not the tensorial inverse of each other. For the same reason, it may also be suspected that the Clarke impedances cannot be obtained by routine methods: that each problem has to be worked out from the ground up.

Kimbark matrices are very similar to the Clarke matrices except that the current and voltage transformation matrices now are not alike in the bottom row. They need not be alike, of course, even though it would be very nice if they turned out to be alike. Evidently, Professor Kimbark encountered some complication in using the Clarke matrices, and in his search for a way out arrived at his results, not stated how. But, even though the current and voltage transformation matrices have been rendered dissimilar, still they are not the inverse of each other, and all difficulty is not avoided: his power equation (13) needs a correction factor of 3/2, and the physical interpretations of the voltage and impedance components are lacking.

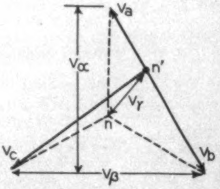

Figure 4. Illustrating V_α, V_β, V_γ

Three things may be said in favor of the modifications made by the writer:

(*a*). The voltages have as simple physical interpretations as the currents.

(*b*). The two matrices are the inverse of each other and therefore the vector power equation is what it ought to be, namely, the sum of the products of the currents with the conjugates of the corresponding voltages:

$$\begin{aligned} P + jQ &= I_\alpha \operatorname{conj} V_\alpha + I_\beta \operatorname{conj} V_\beta + I_\gamma \operatorname{conj} V_\gamma \\ &= I_a \operatorname{conj} V_a + I_b \operatorname{conj} V_b + I_c \operatorname{conj} V_c \end{aligned} \quad (9)$$

(*c*). All of the formulas developed for various problems in any system of components can be transformed to the present system with the help of a single appropriate transformation matrix and its inverse. For instance, all of the formulas of the Fortescue system, for the currents, voltages, and impedances of any problem, can be transformed to the present system with the help of the following single matrix (and its inverse), in which $m = 1, 2, 0$ refer to the Fortescue components; and $\mu = \alpha, \beta, \gamma$, to the Clarke components:

$$A_\mu{}^m = \begin{array}{c|c|c|c} \mu \diagdown m & 1 & 2 & 0 \\ \hline \alpha & 1 & 1 & 1 \\ \hline \beta & -\dfrac{1+\sqrt{3}j}{2} & \dfrac{1+\sqrt{3}j}{2} & 1 \\ \hline \gamma & 0 & 0 & 3 \end{array} \quad (10)$$

The statements by Miss Clarke and Professor Kimbark that the impedances of the new system involve mutuals, and in generators nonreciprocal mutuals, makes me wonder whether some further fundamental research in this system of co-ordinates may not be justified, to find a modification which will avoid that complication. Possible transformations of co-ordinates, that is, possible equivalent systems, are infinite in number; and we are justified in being optimistic. What we need is a clue as to the direction in which the kind of tool we want is to be found.

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* For the method of inversion of a matrix see Kron's new book, "Tensor Analysis of Networks."

Finally, in spite of some who are doubtful the electrical engineering profession will in time come to realize that *the method of reasoning called tensor analysis is a very valuable tool.*

Edith Clarke (General Electric Company, Schenectady, N. Y.): Professor Kimbark has given an excellent presentation of a method of solving three-phase unbalanced systems by means of three sets of components different from symmetrical components. He is to be congratulated on his systematic and logical treatment of this timely subject. Undoubtedly, the components discussed in this paper will be extensively used, since their use greatly simplifies the solution of many problems, not only those dealing with steady state conditions but with transient conditions as well.

With this in mind and realizing the advantages of a standardized notation, I am prompted to discuss the title and notation of the paper:

The title "Two-Phase Co-ordinates of a Three-Phase Circuit" is not descriptive of a circuit in which there are zero-sequence components. In reference 8 the title "Modified Symmetrical Components" was used. The objection to this title is that it does not specify how the symmetrical components are modified.

In references 3, 5, 6, and 8, the components are called α, β, and 0 components, where

α components are positive- plus negative-sequence components, and are therefore the same as x components.

β components are positive- minus negative-sequence components turned backward 90 degrees, and are therefore y components with reversed signs. β components conform to the notation in reference 2.

0 components are zero-sequence components. z components of voltage are zero-sequence voltages. z components of current are twice zero-sequence currents, z impedances are one-half zero-sequence impedances.

The advantages in retaining the well-established zero-sequence components and conforming to the notation of reference 2 appear to me to outweigh the advantages of the y and z components. My preference is for α, β, and 0 components as defined above with the title of "α, β, 0 components," but I should welcome a more descriptive title and a notation standardized by the Institute.

Troy D. Graybeal (Massachusetts Institute of Technology, Cambridge): Mr. Kimbark has given a lucid account of a mathematical transformation well adapted to solving certain types of unbalanced three-phase circuits. His physical interpretation of the transformed currents and voltages is highly commendable. A few words of this nature do more to clarify ideas for one unfamiliar with the subject than do pages of description and mathematical formulas.

The illustrative examples are pertinent in pointing out the type of problem that can be handled by this method. Undoubtedly, the equivalent circuits given in the appendix would be of great value to anyone applying these co-ordinates to a problem set up on a network analyzer. Yet in a method of this type there is often the disappointing lack of the "nicety" of symmetry. The factor $^3/_2$ coming into the expression for power and the factor 2 in the expression for I destroy the symmetry that is desirable in any set of working formulas.

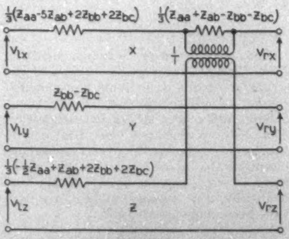
I rather disfavor the title "two-phase components." It gives the impression that the three-phase voltages (or currents) are expressible by two components which are two-phase. Actually there are three components, one of which is the well-known zero component divided by two. It does not seem proper to speak of a set of voltages as two-phase when a zero component is involved. In addition, the two remaining components V_x and V_y, do not represent a set of two-phase voltages in the ordinary sense unless $V^- = 0$ or $V^+ = 0$. This relation exists only for balanced impedances in all three phases. These conditions are contrary to the cases where this transformation would be applied.

It seems to me that Miss Clarke's method of representation where $V_\alpha = V^+ + V^-$ and $V_\beta = V^+ - V^-$ leads to somewhat simpler results than do the use of V_x and V_y. The introduction of the j in the y components appears to introduce complexities in the relations between the different voltages and currents so that transformer ratios like $1:j$ are needed in some of the equivalent circuits. Whereas transformer ratios of this kind may be treated easily mathematically, they are not easily represented on a network analyzer.

Edward Helwith (Gibbs and Hill, Inc., New York, N. Y.): This comment on Doctor Kimbark's paper "Two-Phase Co-ordinates of a Three-Phase Circuit" is a presentation of some of his conclusions in matrix form, illustrating an approach which is probably standard for cases of substituted variables.

Starting with the most general three-phase circuit

$$\left.\begin{aligned} V_a &= Z_{aa}I_a + Z_{ab}I_b + Z_{ac}I_c \\ V_b &= Z_{ba}I_a + Z_{bb}I_b + Z_{bc}I_c \\ V_c &= Z_{ca}I_a + Z_{cb}I_b + Z_{cc}I_c \end{aligned}\right\} \qquad (1)$$



$\frac{1}{3}(Z_{aa}-5Z_{ab}+2Z_{bb}+2Z_{bc})$
$\frac{1}{3}(Z_{aa}+Z_{ab}-Z_{bb}-Z_{bc})$
V_{lx}
x
1 : 1
V_{rx}
$Z_{bb}-Z_{bc}$
V_{ly}
Y
V_{ry}
$\frac{1}{3}(-\frac{1}{2}Z_{aa}+Z_{ab}+2Z_{bb}+2Z_{bc})$
V_{lz}
Z
V_{rz}

Figure 5

We define

$$V = \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \quad I = \begin{vmatrix} I_a \\ I_b \\ I_c \end{vmatrix} \quad Z = \begin{vmatrix} Z_{aa}Z_{ab}Z_{ac} \\ Z_{ba}Z_{bb}Z_{bc} \\ Z_{ca}Z_{cb}Z_{cc} \end{vmatrix} \quad (2)$$

and write $V = Z{\cdot}I$.

We define

$$V' = \begin{vmatrix} V_x \\ V_y \\ V_z \end{vmatrix} \quad I' = \begin{vmatrix} I_x \\ I_y \\ I_z \end{vmatrix} \quad Z' = \begin{vmatrix} Z_{xx}Z_{xy}Z_{xz} \\ Z_{yx}Z_{yy}Z_{yz} \\ Z_{zx}Z_{zy}Z_{zz} \end{vmatrix} \quad (3)$$

To relate the systems to each other we put

$$\left.\begin{aligned} V_x &= \frac{1}{3}(2V_a - V_b - V_c) \\ V_y &= \frac{1}{\sqrt{3}}(0V_a - V_b + V_c) \\ V_z &= \frac{1}{3}(V_a + V_b + V_c) \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} I_x &= \frac{1}{3}(2I_a - I_b - I_c) \\ I_y &= \frac{1}{\sqrt{3}}(0I_a - I_b + I_c) \\ I_z &= \frac{2}{3}(I_a + I_b + I_c) \end{aligned}\right\} \qquad (5)$$

which in matrix notation is

$$\begin{vmatrix} V_x \\ V_y \\ V_z \end{vmatrix} = \begin{vmatrix} 2y^2 & -g^2 & -g^2 \\ 0 & -g & g \\ g^2 & g^2 & g^2 \end{vmatrix} \cdot \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \qquad (6)$$

(letting $1/\sqrt{3}$ be g for brevity) wherein the square matrix, called C_v, is an operator or transformation which through multiplication converts the last matrix into the set of equations (4). Equation 6 says $V' = C_v{\cdot}V$

Similarly for (5) we write $I' = C_I{\cdot}I$ where

$$C_I = \begin{vmatrix} 2g^2 & -g^2 & -g^2 \\ 0 & -g & g \\ 2g^2 & 2g^2 & 2g^2 \end{vmatrix}$$

differing from C_v in the last row.

We postulate that Ohm's law must hold for the two-phase co-ordinates ($V' = Z'I'$) thereby fixing the uniqueness of Z' in terms of Z. To find Z':

$$I' = C_I{\cdot}I$$
$$V' = C_v{\cdot}V$$

so

$$I = C_I^{-1}{\cdot}I'$$
$$V = C_v^{-1}{\cdot}V'$$

and substituting these in $V = Z{\cdot}I$ we get

$$C_v^{-1}{\cdot}V' = Z{\cdot}C_I^{-1}{\cdot}I'$$

or

$$C_v{\cdot}C_v^{-1}{\cdot}V' = V' = C_v{\cdot}Z{\cdot}C_I^{-1}{\cdot}I'$$

But by Ohm's law $V' = Z'I'$ so

$$Z' = C_v{\cdot}Z{\cdot}C_I^{-1} \qquad (7)$$

where C_I^{-1} is the inverse of C_I.

$$C_I^{-1} = \begin{vmatrix} 1 & 0 & 1/2 \\ -1/2 & -1/2g & 1/2 \\ -1/2 & 1/2g & 1/2 \end{vmatrix}$$

(see Doctor Kimbark's equation 3).

Operating on the Z of (2) as indicated in (7) we get $Z' = C_v Z \cdot C_I^{-1} =$

$$\frac{1}{2}\left|\begin{matrix} g^2\left\{\begin{matrix} 4Z_{aa} - 2Z_{ab} - 2Z_{ac} \\ -2Z_{ba} + Z_{bb} + Z_{bc} \\ -2Z_{ca} + Z_{cb} + Z_{cc} \end{matrix}\right\} & g\left\{\begin{matrix} 0 - 2Z_{ab} + 2Z_{ac} \\ +0 + Z_{bb} - Z_{bc} \\ +0 + Z_{cb} - Z_{cc} \end{matrix}\right\} & g^2\left\{\begin{matrix} 2Z_{aa} + 2Z_{ab} + 2Z_{ac} \\ -Z_{ba} - Z_{bb} - Z_{bc} \\ -Z_{ca} - Z_{cb} - Z_{cc} \end{matrix}\right\} \\ g\left\{\begin{matrix} 0 \quad +0 \quad +0 \\ -2Z_{ba} + Z_{bb} + Z_{bc} \\ +2Z_{ca} - Z_{cb} - Z_{cc} \end{matrix}\right\} & \left\{\begin{matrix} 0 + 0 \quad + 0 \\ +0 + Z_{bb} - Z_{bc} \\ +0 - Z_{cb} + Z_{cc} \end{matrix}\right\} & g\left\{\begin{matrix} 0 \quad +0 \quad +0 \\ -Z_{ba} - Z_{bb} - Z_{bc} \\ +Z_{ca} + Z_{cb} + Z_{cc} \end{matrix}\right\} \\ g^2\left\{\begin{matrix} 2Z_{aa} - Z_{ab} - Z_{ac} \\ +2Z_{ba} - Z_{bb} - Z_{bc} \\ +2Z_{ca} - Z_{cb} - Z_{cc} \end{matrix}\right\} & g\left\{\begin{matrix} 0 - Z_{ab} + Z_{ac} \\ +0 - Z_{bb} + Z_{bc} \\ +0 - Z_{cb} + Z_{cc} \end{matrix}\right\} & g^2\left\{\begin{matrix} Z_{aa} + Z_{ab} + Z_{ac} \\ +Z_{ba} + Z_{bb} + Z_{bc} \\ +Z_{ca} + Z_{cb} + Z_{cc} \end{matrix}\right\} \end{matrix}\right| \qquad (8)$$

where the elements are respectively

$$\left|\begin{matrix} Z_{xx}Z_{xy}Z_{xz} \\ Z_{yx}Z_{yy}Z_{yz} \\ Z_{zx}Z_{zy}Z_{zz} \end{matrix}\right|$$

This is the most general case possible, in which all impedances are permitted to be unequal and nonreciprocal. The simpler forms used in most problems can be found from this by applying the simplifying equalities provided by the data of the problem. Thus, for static circuits all mutuals are reciprocal, while for balanced circuits various impedances are equal.

Take as an illustration an untransposed transmission line symmetrical about its center wire a

$Z_{bb} = Z_{cc}$, $Z_{ab} = Z_{ba} = Z_{ac} = Z_{ca}$, $Z_{bc} = Z_{cb}$

The impedance matrix (8) reduces to

$$Z' = \left|\begin{matrix} g^2(2Z_{aa} - 4Z_{ab} + Z_{bb} + Z_{bc}) & 0 & g^2(Z_{aa} + Z_{ab} - Z_{bb} - Z_{bc}) \\ 0 & (Z_{bb} - Z_{bc}) & 0 \\ g^2(Z_{aa} + Z_{ab} - Z_{bb} - Z_{bc}) & 0 & g^2({}^1/_2Z_{aa} + 2Z_{ab} + Z_{bb} + Z_{bc} \end{matrix}\right| \qquad (9)$$

Note that circuit y is independent, while circuits x and z are coupled by a single mutual. The other mutuals have vanished (which was the reason for using the transformation). The equivalent circuit (figure 2 of Doctor Kimbark's paper) is suitable for solving by elementary methods or setting up on a calculating board (figure 5 of this discussion).

The demonstration that $Z' = C_v Z \cdot C_I^{-1}$ is of course general, and this equation will give the new impedances for any system of substituted variables.

R. D. Evans and **J. E. Hobson** (both of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Professor Kimbark's paper is of considerable interest in that he has given a competent discussion of a method which might be suggested as a substitute for the familiar method of symmetrical components. We believe the results of his investigation show that the new components may be useful for a small class of specialized problems as an auxiliary tool to supplement symmetrical components, but that the proposed system of components offers no fundamental advantage which will justify considering it as a replacement for symmetrical components in general. We agree with what we believe is Professor Kimbark's intent, that the method appears to be for limited rather than for general use, and of immediate value to the specialist in circuit theory rather than to the practical engineer handling system problems.

The solution of unbalanced circuit problems is now generally obtained by the method of symmetrical components using the sets of components designated as positive, negative, and zero sequence. The solutions are commonly carried out with the aid of the conception of the sequence network,[1] first introduced in 1925. The connection of these networks is rather simple for the ordinary unbalances to which a symmetrical system may be subjected. However, for the more complicated unbalances, such as may be described by the terms "unbalanced faults on unsymmetrical systems" and "multiple unbalances," the interconnections between networks become quite complicated. This problem was investigated in a previous paper by Professor Kimbark[2] who provided a solution for a number of these cases by introducing mutual coupling between the networks. An investigation revealed that the components, described in this paper as "two-phase co-ordinates," do simplify the coupling between networks for certain types of unbalances. The question naturally arises as to the practical value of the method. Stated in another way, does the method offer sufficient promise as to justify the practical engineer becoming as familiar with it as he has with the method of symmetrical components?

In our experience and opinion the vast majority of unbalanced-circuit problems deal with faults on a symmetrical system. For such problems the use of symmetrical components gives the simplest set of components because, (1) the positive-sequence network is the system network for the normal operating condition, (2) the negative-sequence network has an interpretation that is readily understood, (3) the use of "two-phase co-ordinates" requires sources of electromotive force associated with two rather than one set of components, and (4) the majority of problems involving machines may be considered on the basis of nonsalient-pole theory; for such cases the negative-sequence system is of particular advantage from the standpoint of the physical conception and from the ease of manipulation.

The question thus becomes that of whether or not the advantage of the method proposed here would justify its use for special problems. For double unbalances and many similar problems it is possible to extend the symmetrical components by analytical methods, as discussed by Edith Clarke,[3] Wagner and Evans,[4] and E. L. Harder.[5] Many times it is possible to resolve the problem into a symmetrical part and add it to the symmetrical system, as discussed by Wagner and Evans,[4] chapter 8. The use of this procedure would permit treating examples 6, 7, 8, and 9 of this paper as special cases for one type of unbalance, as in the manner employed by Harder.[5]

Professor Kimbark has indicated that unbalanced faults on an unsymmetrical distribution system provide the most frequently occurring practical problem for which the method would be applicable. Such problems as they occur practically, usually permit the use of a single source and also the use of the same impedance in the supply for both positive and negative sequence. Such a system may be readily solved with the a-c network calculator set up to represent the three-phase networks. Such a procedure has been found advantageous for the study of transients and has been used to a considerable extent.[6]

It should be pointed out that some of the special cases discussed by Professor Kimbark may be solved with less, or with no greater, complexity by the use of symmetrical components. The two-phase method appears to be advantageous for cases when the circuit (1) does not permit the flow of zero-sequence currents and (2) is symmetrical with respect to one phase. For example, the method is advantageous for systems involving transformers connected open delta/open delta but offers little advantage for the open delta/open star connection, for the open delta/open delta autotransformer connection, or for the open delta/open delta connection for the apexes of the two V's connected and common to both circuits. For either of the cases just mentioned the use of either system of co-ordinates will involve mutual coupling with the zero-sequence network.

The term "Two-Phase Co-ordinates of a Three-Phase Circuit" suggests that the method is simpler than symmetrical components with its three sets of components. We recognize the difficulty in finding suitable names for such methods, but we believe the name chosen is not altogether appropriate since there is included a third set of components not associated with a two-phase system, and since the voltages and currents of the two-phase system set up in this paper do not always bear 90-degree relationships. We believe it is more difficult to get a clear physical conception of the two-phase co-ordinate networks than for the conventional and accepted positive- and negative-sequence networks. Furthermore, it is very unfortunate that the co-ordinate system set up here has different equations for resolving voltages and currents into their zero-sequence components, and that the zero-sequence co-ordinate system is so nearly the same as the zero-sequence system of symmetrical components without being identical with it. The familiar zero-sequence system could have been retained by appropriate modification of the definitions for the other sequence systems.

In conclusion, we feel Professor Kimbark's investigation has been quite worth while, that his analysis is thorough and complete, and that he has presented the results quite clearly. However, we do not think the system of co-ordinates proposed will in any sense replace symmetrical components for general use, although specialists in system calculations may find occasional use for the system of "two-phase co-ordinates" as a supplemental tool to symmetrical components.

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S. Austen Stigant (London, England): Accepting the stated definition of the 0, α, and β currents, an approach to their study, which is perhaps more direct than that given in the paper, is as follows. In a three-phase system of conductors the 0, α, and β currents are distributed as shown in figure 6 of this discussion from which,

$$\left.\begin{aligned} I_a &= I_0 + I_\alpha \\ I_b &= I_0 - 1/2I_\alpha + I_\beta \\ I_c &= I_0 - 1/2I_\alpha - I_\beta \end{aligned}\right\} \quad (1)$$

or in matrix notation $[I_n] = [M_1]\cdot[I_\gamma]$, that is,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1, & 1, & 0 \\ 1, & -1/2, & 1 \\ 1, & -1/2, & -1 \end{bmatrix} \cdot \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \quad (2)$$

Then, $[I_\gamma] = [M_1]^{-1}\cdot[I_n]$, that is,

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} 1/3, & 1/3, & 1/3 \\ 2/3, & -1/3, & -1/3 \\ 0, & 1/2, & -1/2 \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3)$$

from which,

$$\left.\begin{aligned} I_0 &= 1/3\,(I_a + I_b + I_c) \\ I_\alpha &= 1/3\,(2I_a - I_b - I_c) \\ I_\beta &= 1/2\,(I_b - I_c) \end{aligned}\right\} \quad (4)$$

The corresponding voltage equations on the basis of line-to-neutral voltages are identical with the foregoing, substituting E (or V) for I, so that,

$$[E_\gamma] = [M_1]^{-1}\cdot[E_m] \quad (5)$$

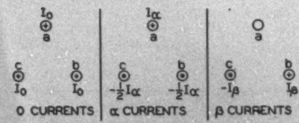

Figure 6

Now,

$$\left.\begin{aligned} [E_m] &= [Z_{mn}]\cdot[I_n] \\ &= [Z_{mn}]\cdot[M_1]\cdot[I_\gamma] \end{aligned}\right\} \quad (6)$$

and,

$$\left.\begin{aligned} &[Z_{mn}]\cdot[M_1] \\ &= \begin{bmatrix} Z_{aa}, & Z_{ab}, & Z_{ac} \\ Z_{ba}, & Z_{bb}, & Z_{bc} \\ Z_{ca}, & Z_{cb}, & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} 1, & 1, & 0 \\ 1, & -1/2, & 1 \\ 1, & -1/2, & -1 \end{bmatrix} \\ &= \begin{bmatrix} Z_{a0}, & Z_{a\alpha}, & Z_{a\beta} \\ Z_{b0}, & Z_{b\alpha}, & Z_{b\beta} \\ Z_{c0}, & Z_{c\alpha}, & Z_{c\beta} \end{bmatrix}, \text{ say.} \end{aligned}\right\} \quad (7)$$

Substituting for $[E_m]$ in (6),

$$\left.\begin{aligned} &[M_1]\cdot[E_\gamma] = [Z_{mn}]\cdot[M_1]\cdot[I_\gamma] \\ &\text{and,} \\ &[E_\gamma] = [M_1]^{-1}\cdot[Z_{mn}]\cdot[M_1]\cdot[I_\gamma] \end{aligned}\right\} \quad (8)$$

so that the new impedance matrix is,

$$\left.\begin{aligned} [Z_{m'n'}] &= [M_1]^{-1}\cdot[Z_{mn}]\cdot[M_1] \\ &= \begin{bmatrix} \frac{1}{3}, & \frac{1}{3}, & \frac{1}{3} \\ \frac{2}{3}, & -\frac{1}{3}, & -\frac{1}{3} \\ 0, & \frac{1}{2}, & -\frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} Z_{a0}, & Z_{a\alpha}, & Z_{a\beta} \\ Z_{b0}, & Z_{b\alpha}, & Z_{b\beta} \\ Z_{c0}, & Z_{c\alpha}, & Z_{c\beta} \end{bmatrix} \\ &= \frac{1}{3}\begin{bmatrix} (Z_{a0} + Z_{b0} + Z_{c0}), & (Z_{a\alpha} + Z_{b\alpha} + Z_{c\alpha}), & (Z_{a\beta} + Z_{b\beta} + Z_{c\beta}) \\ (2Z_{a0} - Z_{b0} - Z_{c0}), & (2Z_{a\alpha} - Z_{b\alpha} - Z_{c\alpha}), & (2Z_{a\beta} - Z_{b\beta} - Z_{c\beta}) \\ \frac{3}{2}(Z_{b0} - Z_{c0}) & , \frac{3}{2}(Z_{b\alpha} - Z_{c\alpha}) & , \frac{3}{2}(Z_{b\beta} - Z_{c\beta}) \end{bmatrix} \end{aligned}\right\} \quad (9)$$

In terms of symmetrical components,

$$\left.\begin{aligned} [E_s] &= [S]^{-1}\cdot[E_m] \\ &= [S]^{-1}\cdot[M_1]\cdot[E_\gamma] \\ &= [M_2]\cdot[E_\gamma] \end{aligned}\right\} \quad (10)$$

where

$$\left.\begin{aligned} [M_2] &= [S]^{-1}\cdot[M_1] \\ &= \frac{1}{3}\begin{bmatrix} 1, & 1, & 1 \\ 1, & h, & h^2 \\ 1, & h^2, & h \end{bmatrix} \cdot \begin{bmatrix} 1, & 1, & 0 \\ 1, & -\frac{1}{2}, & 1 \\ 1, & -\frac{1}{2}, & -1 \end{bmatrix} \\ &= \begin{bmatrix} 1, & 0, & 0 \\ 0, & \frac{1}{2}, & j\frac{1}{\sqrt{3}} \\ 0, & \frac{1}{2}, & -j\frac{1}{\sqrt{3}} \end{bmatrix} \end{aligned}\right\} \quad (11)$$

and

$$[M_2]^{-1} = \begin{bmatrix} 1, & 0, & 0 \\ 0, & 1, & 1 \\ 0, & -j\frac{\sqrt{3}}{2}, & j\frac{\sqrt{3}}{2} \end{bmatrix} \quad (12)$$

Also,

$$\left.\begin{aligned} &[E_s] = [Z_s]\cdot[I_s] \text{ where} \\ &[Z_s] = \begin{bmatrix} Z_{00}, & Z_{01}, & Z_{02} \\ Z_{10}, & Z_{11}, & Z_{12} \\ Z_{20}, & Z_{21}, & Z_{22} \end{bmatrix} \end{aligned}\right\} \quad (13)$$

so that,

$$[M_2]\cdot[E_\gamma] = [Z_s]\cdot[M_2]\cdot[I\gamma] \text{ and}$$

$$[E_\gamma] = [M_2]^{-1}\cdot[Z_s]\cdot[M_2]\cdot[I\gamma]$$

from which equation 14 is obtained.

The mutual impedances of the symmetrical component impedance matrix $[Z_s]$ ($=[S]^{-1}\cdot[Z_{mn}]\cdot[S]$) are, in general, nonreciprocal. However, when $Z_{11} = Z_{22}$ the mutual impedances of matrix 14 are reciprocal numerically if we multiply the first column of (14) by $^1/_2$ and the third column by $^3/_4$. We must then define I_0, I_α, and I_β as

$$\left.\begin{aligned} I_0 &= \tfrac{2}{3}\,(I_a + I_b + I_c) \\ I_\alpha &= \tfrac{2}{3}\,(2I_a - I_b - I_c) \\ I_\beta &= \tfrac{1}{3}\,(I_b - I_c) \end{aligned}\right\} \quad (15)$$

The fact that under these circumstances the mutual impedances of matrix 14 and hence (9) are reciprocal, that is, matrices (9) and (14) are virtually symmetrical, is of itself, of no use, since by the ordinary method of calculation $[Z_{mn}]$ is symmetrical in nearly all practical cases. But if, in addition, the network is symmetrical about phase *a* the equivalent impedance matrix (9) contains only one pair of reciprocal mutual impedances, all other mutual impedances being zero. Let

$$Z_{bb} = Z_{cc}, \quad Z_{ab} = Z_{ac} \text{ and}$$
$$Z_{ab} = Z_{ba}, \quad Z_{bc} = Z_{cb}, \quad Z_{ca} = Z_{ac}$$

Then,

$$\left.\begin{aligned} Z_{a0} &= Z_{aa} + 2Z_{ab} \\ Z_{b0} &= Z_{bb} + Z_{ab} + Z_{bc} \\ Z_{c0} &= Z_{bb} + Z_{ab} + Z_{bc} = Z_{b0} \\ \\ Z_{a\alpha} &= Z_{aa} - Z_{ab} \\ Z_{b\alpha} &= Z_{ab} - \frac{1}{2}(Z_{bb} + Z_{bc}) \\ Z_{c\alpha} &= Z_{ab} - \frac{1}{2}(Z_{bb} + Z_{bc}) = Z_{b\alpha} \\ \\ Z_{a\beta} &= 0 \\ Z_{b\beta} &= Z_{bb} - Z_{bc} \\ Z_{c\beta} &= Z_{bc} - Z_{bb} = -Z_{b\beta} \end{aligned}\right\} \quad (16)$$

$$\left.\begin{aligned}
[Z_{m'n'}] &= [M_2]^{-1}\cdot[Z_s]\cdot[M_2] \\
&= \begin{bmatrix} 1, & 0\,, & 0 \\ 0, & 1\,, & 1 \\ 0, & -j\frac{\sqrt{3}}{2}, & j\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} Z_{00}, & Z_{01}, & Z_{02} \\ Z_{10}, & Z_{11}, & Z_{12} \\ Z_{20}, & Z_{21}, & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} 1, & 0, & 0 \\ 0, & \frac{1}{2}, & j\frac{1}{\sqrt{3}} \\ 0, & \frac{1}{2}, & -j\frac{1}{\sqrt{3}} \end{bmatrix} \\
&= \begin{bmatrix} Z_{00} & , \frac{1}{2}(Z_{01}+Z_{02}) & , j\frac{1}{\sqrt{3}}(Z_{01}-Z_{02}) \\ Z_{10}+Z_{20} & , \frac{1}{2}(Z_{11}+Z_{21}+Z_{12}+Z_{22}), & j\frac{1}{\sqrt{3}}(Z_{11}+Z_{21}-Z_{12}-Z_{22}) \\ j\frac{\sqrt{3}}{2}(Z_{20}-Z_{10}), & j\frac{\sqrt{3}}{4}(Z_{21}+Z_{22}-Z_{11}-Z_{12}), & \frac{1}{2}(Z_{11}+Z_{22}-Z_{12}-Z_{21}) \end{bmatrix}
\end{aligned}\right\} \quad (14)$$

Therefore from (9) the new impedance matrix becomes,

$$[Z_{m'n'}] = \frac{1}{3}\begin{bmatrix} Z_{aa}+2Z_{bb}+4Z_{ab}+2Z_{bc}, & Z_{aa}+Z_{ab}-(Z_{bb}+Z_{bc}), & 0 \\ 2\{Z_{aa}+Z_{ab}-(Z_{bb}+Z_{bc})\}, & 2(Z_{aa}-2Z_{ab})+Z_{bb}+Z_{bc}, & 0 \\ 0 & , \quad 0 & , 3(Z_{bb}-Z_{bc}) \end{bmatrix} \quad (17)$$

Or dividing the first column by 2 and defining I_0 as in (15), and I_α and I_β as in (4), the new impedance matrix is,

$$\frac{1}{3}\begin{bmatrix} \frac{Z_{aa}}{2}+Z_{bb}+2Z_{ab}+Z_{bc}, & Z_{aa}+Z_{ab}-(Z_{bb}+Z_{bc}), & 0 \\ Z_{aa}+Z_{ab}-(Z_{bb}+Z_{bc}), & 2(Z_{aa}-2Z_{ab})+Z_{bb}+Z_{bc}, & 0 \\ 0 & , \quad 0 & , \quad 3(Z_{bb}-Z_{bc}) \end{bmatrix} \quad (18)$$

where there is only one pair of mutual impedances and these are reciprocal.

W. A. Lewis (Cornell University, Ithaca, N. Y.): In the other discussions of this paper it is pointed out that the title "Two-Phase Co-ordinates" is not truly representative of the type of co-ordinates, and that a more suitable name should be applied. In view of the fact that these co-ordinates are not symmetrical, it would not be appropriate to call them a variety of symmetrical components even though they are conceived in terms of symmetrical component quantities. In view of the fact that the basic components are normally at right angles, I would like to suggest the name "quadric components."

It must be definitely borne in mind that to represent a three-phase system without restriction, there must be three components, each possessing both magnitude and direction, in order to comply with the necessary degrees of freedom, and it seems extremely important that the name used should not suggest there are less than three components. If an entirely new name is used, but one which is to some extent descriptive, it would seem that the principal objections are overcome.

Edward W. Kimbark: Most of the discussion can be grouped under two heads: first, that which concerns the field of application of the new co-ordinates; second, that which concerns their name, notation, and form.

With respect to the field of application, I agree with Evans and Hobson that the new method is not intended to supplant symmetrical components. On the other hand, I cannot agree with them that it is of such little practical value that the engineer who knows symmetrical components should not bother to become acquainted with it. Some problems are solved more easily by symmetrical co-ordinates, some by two-phase co-ordinates, and some with equal ease (or difficulty) by either method. Several practical problems, not given in the paper, to which two-phase co-ordinates are applied advantageously have come to my attention, and future experience with the method should widen its field of use. The new co-ordinates are not hard to learn, because familiarity with the method of symmetrical components has already accustomed engineers to thinking in terms of substitute currents and voltages and substitute networks. Becoming familiar with a second substitution is a smaller step than grasping the concept of using any substitution. Mr. Evans and his associates, by evolving a practical, everyday working tool from an ingenious but abstruse mathematical transformation, have already broken the hard ground.

The transformer connections which Evans and Hobson cite as ones in which two-phase co-ordinates offer little advantage over symmetrical co-ordinates are poorly chosen to prove their point. As they say, the use of either co-ordinates involves mutual coupling with the zero-sequence or z network. However, they fail to point out that in the equivalent circuits of these transformers in symmetrical co-ordinates all three sequence networks are coupled together, whereas in two-phase co-ordinates only the x and z networks are coupled, the y network being entirely independent. For this reason the equivalent circuits in question are much simpler in two-phase co-ordinates than in symmetrical co-ordinates.

A disadvantage of the method of two-phase co-ordinates, stated in the paper, is that both x and y networks contain sources of electromotive force. This disadvantage disappears, however, in the type of problems to which the method would be applied most frequently—problems in three-phase circuits symmetrical with respect to one phase—because in such cases the y network is independent. This fact enables us to make one network, set up on a calculating board, do double duty—first as the x network, then, with slight change, as the y network.

Let us turn now to the second aspect of the discussion, dealing with name, notation, and form. There seems to be general dissatisfaction with the name "two-phase co-ordinates." The objections to it given are: (1) that the name implies that three independent variables are replaced by two; and (2) that the two-phase co-ordinates of an *unbalanced* set of three-phase currents or voltages are not equal and in quadrature like a *balanced* set of two-phase currents or voltages. I feel that the name is appropriate because the x and y networks may be considered jointly to constitute a two-phase network equivalent to the original three-phase network after the zero-sequence quantities have been abstracted from it. The two-phase components of a balanced positive-sequence set of three-phase vectors form a balanced two-phase set of vectors of phase order y, x. Reversing the phase order of the three-phase vectors reverses the phase order of their two-phase components. The two-phase components of an unbalanced three-phase set of vectors form an unbalanced two-phase set.

But, as the discussion has shown amply that the name "two-phase co-ordinates" leads to misunderstanding, another name should be considered. The name "quadric components," proposed by Doctor Lewis, does not seem entirely appropriate, as the dictionary's definition of "quadric" is "(Math.) Of the second degree." The word "quadrature" more nearly fits the intended meaning, but is open to one of the expressed objections to the name "two-phase" even more than the latter is; namely, that the two-phase components of unbalanced three-phase vectors may not be in quadrature. In the absence of an acceptable descriptive name, a personal name could well be used, and the designation "Clarke components," proposed by Mr. Boyajian, is highly appropriate.

The notation to be used in denoting the three substitute networks is largely a matter of taste, and there is no disputing about tastes. I prefer roman letters (such as x, y, z) to Greek letters (such as α, β, γ) because the latter are not found on many typewriters. Besides, the Greek α is easily confused with the roman a, often used in the same equations to denote a phase. Letters x and y, by suggesting the axes of a rectangular co-ordinate system, help one to remember the positions of the vectors representing the two-phase components of balanced positive-sequence three-phase vectors; while z follows in alphabetical order and suggests zero sequence. Obviously, it would not be wise to use subscript 0 for components similar to, but not identical to, the zero-sequence components of symmetrical co-ordinates.

The use of matrix notation was avoided in the paper in the belief that it would be a hindrance rather than a help to the average reader. However, for readers interested in matrix and tensor methods, the discussions of Boyajian, Helwith, and Stigant form a valuable supplement to the paper.

In defining the new components there are many alternative forms differing by constant factors. That is, we may have in place of equations 2 of the paper:

$$
\begin{aligned}
I_x &= k_x(2I_a - I_b - I_c)\\
I_y &= k_y(I_b - I_c)\\
I_z &= k_z(I_a + I_b + I_c)
\end{aligned}
$$

$$
\begin{aligned}
V_x &= K_x(2V_a - V_b - V_c)\\
V_y &= K_y(V_b - V_c)\\
V_z &= K_z(V_a + V_b + V_c)
\end{aligned}
$$

where k_x, k_y, k_z, K_x, K_y, K_z may be chosen in various ways. Mr. Boyajian has proposed a new form of the components which has considerable merit. The considerations bearing on the choice of the k's and K's may be listed as follows (not necessarily in order of importance):

1. (*a*) Complete or (*b*) partial invariance of power. By "complete invariance" of power, I mean that the vector power of a three-phase circuit is given in terms of substitute variables by $\Sigma(I_m \text{ conj } V_m)$ where $m = x, y, z$ or α, β, γ; and by "partial invariance" that it is given by $C\Sigma(Ie_m \text{ conj } V_m)$, where C is a constant. I consider partial invariance essential for the representation of unbalances by means of connections between the substitute networks. The additional step of complete invariance seems less necessary from a practical standpoint, though it is convenient in cases where a three-phase system is to be represented partially on a three-phase basis and partially in two-phase co-ordinates. The presence of the factor $C = 3$ in the power equation in symmetrical components has caused no particular difficulty; neither should a factor 3/2 in the corresponding equation for two-phase components cause any difficulty.

2. Same transformation for voltage as for current. This makes the formulas easier to remember.

3. Simple numerical coefficients (k's and K's) in the transformations. This facilitates both numerical calculation and visualization.

4. Simple transformer ratios (preferably one to one) in the connections between the substitute networks, especially the x and z networks, in the equivalent circuits of the commonest types of unbalance. This gives simple equivalent circuits, especially for calculating-board work.

5. Simple relation of the new components to symmetrical components. This takes advantage of the engineers' present familiarity with symmetrical components.

Unfortunately, the specifications given above are somewhat contradictory and cannot all be met by the same set of components. Therefore, one's choice of a particular set will depend upon the relative weight given to the several items in accord with one's opinion as to which contribute most to the mathematical consistency, nicety, or symmetry, and to the practical usability. With the aid of Mr. Boyajian's table of three forms of transformation matrix (Clarke, Kimbark, and Boyajian) let us see how well each form meets the specifications listed above. A fourth form, the "tensor form," given by Concordia,[3] will be considered also.

1. The Clarke form does not give invariance of power, the Kimbark form gives partial invariance, the Boyajian and Concordia forms give complete invariance.

2. The Clarke and Concordia forms have the voltage transformations identical to the current transformations; the Kimbark and Boyajian forms do not.

3. The Boyajian form has the simplest numerical coefficients and simplest physical interpretation, the Concordia form, the least simple.

4. The Concordia form leads to transformer ratios $1:\sqrt{2}$ in the coupling between substitute networks of the equivalent circuit of such simple unbalances as a line-to-ground short circuit or an open circuit in one wire. The Clarke form gives nonreciprocal coupling with the zero-sequence network. Ratios of transformers connecting the α and γ networks of the Boyajian form differ by a factor of 3/2 from those connecting the x and z networks of the Kimbark form.

5. The Clarke form is most closely related to symmetrical components, the Boyajian form least closely related.

It is true, as Mr. Boyajian says, that the currents, voltages, and impedances in his form of the co-ordinates have simple physical interpretations. As I do not believe that he has made the interpretation of these impedances clear in his discussion, I should like to amplify this point by the following statements:

$Y_{\alpha\alpha}$ is the admittance measured from terminal a to terminals b and c joined together.

$Y_{\beta\beta}$ is the admittance measured from terminal b to terminal c with terminal a open.

$Y_{\gamma\gamma}$ is the admittance measured from terminals a, b, c joined together to ground or neutral.

The corresponding statements for *impedance* are not true unless the substitute networks are independent, for otherwise the elements of the impedance matrix are not the reciprocals of the corresponding elements of the admittance matrix.

The self-admittances for the Kimbark form are equal to those of the Boyajian form multiplied by constants.

The Boyajian α and β impedances of a balanced static three-phase circuit differ from each other and from the positive-sequence impedance. The relations are $Z_{\alpha\alpha} = (3/2)Z_{11}$, $Z_{\beta\beta} = 2Z_{11}$, and $Z_{\gamma\gamma} = (1/3)Z_{00}$. Whether or not this disadvantage outweighs the advantage of simpler physical interpretation (simpler numerical coefficients) is hard to say.

After considering the discussion on name, notation, and form, my inclination is to recommend the following: Name—Clarke components, co-ordinates, or transformation. Notation—x, y, z. Form—Boyajian or Kimbark, pending investigation of equivalent circuits in the Boyajian system.

In concluding, I express the hope that further research in circuit transformations will show a general method of finding a transformation to eliminate or minimize the coupling between substitute networks in any given case. In such research, matrix or tensor methods will no doubt be useful and perhaps even essential.

Discussions

Of AIEE Papers—as Recommended for Publication by Technical Committees

ON THIS and the following three pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the AIEE Pacific Coast convention, Portland, Ore., August 9–12, 1938, and at the AIEE winter convention, New York, N. Y., January 23–27, 1939. These discussions were not available for correlation with their respective papers at the time the papers were published.

Low-Gas-Pressure Cable

Discussion and author's closure of a paper by G. B. Shanklin, presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939, and published in AIEE TRANSACTIONS, 1939 (July section) pages 307–15. Other discussion was published on pages 315–18.

K. S. Wyatt (Enfield Cable Works, Ltd., Enfield, England): The theme of this highly interesting paper is in contrast to that of an earlier one[1] by the same author, for in the latter he showed the benefit of getting out and keeping out all gas spaces from the insulation, whereas here he shows the benefit of putting gas into the insulation. At about the same time that this paper, suggesting that solid cable is inadequate at 40 kv and below, was being delivered in New York, another paper[2] was being delivered in London, showing that solid cable was satisfactory at 60 kv for maximum temperatures of 75 degrees centigrade, and should even be considered for 132 kv.

For the last 40 years improvement in high-voltage cables has been achieved by getting more and more gas and vacuous spaces out of cable insulation, and more oil in: this is true for solid cable and for extra-high-voltage cable such as the oil-filled cable and the pressure cable. Now the author advocates reversing these principles and pushing oil out of the cable insulation and gas in, at least for cables up to 40 kv. Those who advocate gas in the insulation and the extinguishing of ionization by pressure on the gas, must show that on a long operating line, pressure can be maintained uniformly throughout the insulation wall both longitudinally and radially. Consider a line two or three miles in length, the contour of which will normally show a continued succession of rises and dips: if oil is not thoroughly drained from the cable, load-cycles will cause it to fill the dips and these will then act as oil seals against longitudinal transmission of gas pressure. As for radial maintenance of pressure, if there is not continuity of gas channel from conductor to sheath owing to the presence of oil which has not drained out, when gas pressure in the filler spaces drops, the gas, dissolved in the insulation under 10 to 40 pounds per square inch pressure, will come out of solution and tend to "bloat out" the insulation, increasing the radial dimensions of voids, and causing more severe ionization. It is imperative that gas flow through the insulation be such that pressure can be maintained at all points during the most rapid cooling cycle likely to be experienced in operation.

Migration of compound from the high points of a long line will leave the insulation with a very high thermal resistivity. It would be of interest if the author would give the actual values for this class of cable. In England it has been common practice to assume a thermal resistivity of 750 thermal ohms per centimeter cube, for cables up to six kv, in comparison with a value of 550 for high-voltage cables. Such a difference has been justified by practical tests and has been attributed to the less compact construction and the inferior impregnation attained in the lower-voltage class. It is difficult to believe that a cable blown out with nitrogen gas would achieve a lower thermal resistance than the former of the two classes mentioned above. This will reduce maximum current carrying capacity.

Since the author takes ionization for granted in this type of cable, it is certain that ionic bombardment of the oil will produce gases, chiefly hydrogen. The latter being admixed with the pressure gas will reduce its minimum ionization potential, even though original values of the pure pressure gas of special composition are quite high.

Experience with vertical ends of three-conductor 24-kv cable, in which compound has migrated downward and air at atmospheric pressure has replaced it, confirms that such cable will operate satisfactorily for years at maximum stresses of 66 volts per mil. Nevertheless, to propose for commercial operation a gas-filled cable design with advance knowledge that ionization takes place in it from the day it is placed in operation, appears to be a bold step. There is also the consideration of the impulse strength of a cable in which ionization is taking place in the gas films between layers.

The 30-degree-centigrade "solid" loss of the experimental cable exhibited by the author has increased in some cases severely. Unfortunately no radial power-factor curves which show up such deterioration so clearly, are given. There are good reasons for such increases. First, hydrogen generated by ionization from the compound, being admixed with the pressure gas, will react with it during discharge to form from carbon dioxide, water; from nitrogen, ammonia and amide compounds; and from special gases containing chlorine, hydrochloric acid. These products in the presence of moisture, which is always present in fibrous insulation in small amounts, undesirably increases dielectric loss. Second, 0.3 per cent O_2 impurity in the pressure gas should react at 2 atmospheres (absolute) at the same rate as 0.6 per cent O_2 at one atmosphere (absolute); and at 15 atmospheres as 4.5 per cent oxygen at one atmosphere. If the loss keeps on increasing year by year, will these cables be economical?

It is difficult to understand from the author's paper the economic advantage of such cable over solid cable, except that the lead sheath is perhaps not worked so much, thus perhaps cutting down the number of water failures. For a given duct size, however, a larger conductor can be used because of the thinner insulation wall.

Exception must be taken to the author's comments regarding the difficulty of reinforcing a cable for high gas pressure. Such reinforcement merely consists of a thin metal tape wound over the lead sheath together with some suitable bedding. If reinforcement has to be applied it is immaterial whether 40 or 200 pounds per square inch gas pressure is employed, somewhat thicker steel tapes of course being used for the higher pressures. The suggested tendency of such a cable to "whip" in manholes if it were present could be overcome quite simply and inexpensively by the inclusion of a metal tape applied with long lay in the reinforcement.

Conflicting nomenclature is employed by the author. In the title the cable is termed "low-gas-pressure cable" and in the conclusions, "gas-filled cable." Actually the term pressure cable was first used by Hochstadter and Bowden,[3] in a paper describing the use of fluid pressure, either gas or liquid, external to the lead sheath of an ordinary solid cable as a means of eliminating ionization and thus permitting operation at not less than double the stress of solid cable. The term appears to have become generally accepted in this sense. Since when oil is fed into an operating cable it is termed "oil filled" it seems reasonable that when compressed gas is fed into the insulation of an operating cable it should be termed "gas filled."

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2. LONG-PERIOD AGING TESTS ON SOLID-TYPE CABLES, **T. R. Scott** and **R. C. Mildner**. IEE, January 1939.

3. *Journal* of the Royal Society of Arts, volume 80, December 11, 1931.

R. C. Mildner (Enfield Cable Works, Ltd., Enfield, England): The thorough and logical series of investigations on low-gas-pressure cables reported by Mr. Shanklin will be studied with keen interest by cable engineers, not only in America but also in many other countries. In all the major cable-manufacturing countries the realization that the satisfactory transmission of large blocks of power at high voltages goes beyond the basic requirement of adequate electrical performance has stimulated intense research activity, which has brought forward many new forms of high-voltage cable. It may well be that the construction sponsored by the author will find its niche in cable practice, and the Consolidated Edison Company deserves commendation for providing so early an opportunity for a trial installation in the field—a requirement which, for final judgment, must always supplement laboratory tests.

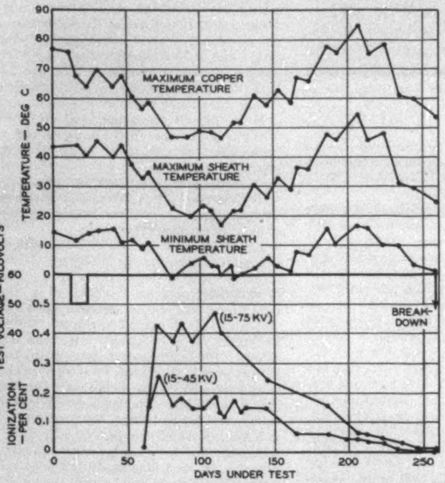

Figure 1. Life-test history—EC. 54/1a

In common with other advocates of the internal-gas-pressure cables, the author has seemed to adopt the viewpoint that the mere application of pressure is capable of defining to a very close degree the stress at which ionization will take place: as a consequence it is claimed that such cables are susceptible of exact engineering design so that it is possible thereby to prevent absolutely any deleterious ionization phenomena under working conditions. General experience and, indeed, the author's own results show that this is by no means the case. The incidence of ionization at any given pressure is both variable, depending upon the previous history of the cable, and indefinite in relation to the stress at which it is initiated. For the case of the low-gas-pressure cable at least, the situation in this respect is in no way dissimilar to that of solid-type cable. Figure 1 of this discussion shows the aging characteristics of a solid-type cable which was reported in a paper presented recently before the British Institution of Electrical Engineers ("Long-Period Aging Tests on Solid-Type Cables," T. R. Scott and R. C. Mildner, paper presented before the transmission section, IEE, January 1939), and it will be seen that it presents quite analogous phenomena of restrained ionization and a "cleaning up" process which operates during a major portion of the life under test. Furthermore, the cable shows a preliminary period during which ionization is entirely absent. In modern well-constructed cable cumulative ionization of the type envisaged by the author does not demonstrate itself at the stresses quoted for low-gas-pressure cable. In the absence, therefore, of quantitative tests it is unwise to assume that pressure-controlled cables of this type are immune from continuous deterioration when subjected to working electrical stresses at which ionization is relatively restrained.

In his discussion of ionization stability the author draws a distinction between positive and negative pressures. It is difficult to see how such a difference can in fact be other than one of degree since, as I assume, such pressures are relative to that of the external atmosphere. A dielectric composed of impregnated paper and gas pockets comprises under voltage a complex series-parallel network, in which the latter components will in general present saturated ionization phenomena. When, under severe conditions of test, secondary ionization sets in, the magnitude of this ionization will often be limited by the capacitive currents which the solid dielectric is capable of transmitting. It is therefore not difficult in solid-type cable to ensure that such ionization is not cumulative but decidedly limited in effect. In normal operation an advantage accrues to the solid-type cable from the fact that the energy associated with saturated ionization at low pressures is less than that bound up with saturated ionization at high pressures.

I believe that it is true to say that most cable engineers in England have accepted the thesis that, in judging test performance in which breakdown occurs by ionization phenomena, it is the value of maximum stress rather than that of average stress which is the limiting factor of operation. Judged on this basis the tests quoted by the author do not seem severe in comparison with those capable of being surmounted by solid cable. Of the cable type adopted by the author only one test to breakdown is mentioned, and this does not compare favorably, even when using the criterion of average stress, with the performance of the best types of modern solid-type cable. Thus in the previously-mentioned paper three distinct cable lengths with 445-mil insulation wall are quoted as having withstood without failure more than 260 days' testing at 134 volts per mil. Now while one cannot say at the moment whether it will prove possible to guarantee such characteristics for every production length of cable, these results do indicate that there would seem to be no obvious intrinsic limitation to the performance of solid-type cable, such as the author implies. It is therefore important to establish what advantages these gas-pressure cable types will have in service operation.

In conclusion I should like the author to express his opinion as to the reason for the variation in the solid loss of his cables at 80 degrees centigrade. An increase in loss may well be explained by the oxygen content of his nitrogen supply, a fact to which reference is made, but the decrease in loss observed, for instance, in lengths 5, 6, 7, and 8, if explained in terms of compound drainage, would suggest that such movements of compound may persist over a period as long as two years. It would appear that the high losses in these cables limit their application at the moment to medium voltages, moderate maximum temperatures, and uncongested cable systems.

G. B. Shanklin: In his discussion, Mr. Wyatt refers to an earlier paper by the same author and cites it as an example of inconsistency. While the author reserves the right to change his mind as the art progresses, this does not exactly apply in this case. If Mr. Wyatt will read the older paper closely, he will find a statement to the effect that gas under pressure in a solid-type cable might be beneficial if some way could be found to prevent this gas from concentrating and forming "dry spots" along the cable length. The present paper describes a design in which we believe this is accomplished.

Mr. Wyatt has raised practical questions regarding uniform maintenance of gas pressure along the cable line in service. Such questions can only be answered by practical field experience. No difficulty has yet been found in controlling pressure in the two installations now in service. We would prefer postponement of a final answer to this question until more field experience is obtained. Regarding maintenance of uniform pressure radially from conductor to sheath, I think Mr. Wyatt is overlooking several important factors. First, the cable is completely gas saturated at the required pressure and automatically tends to maintain this pressure at all points in the cross section. Second, with even the most rapid cooling cycle the drop in gas pressure in the feed channels is relatively small. We are not worried about the difficulties of maintaining uniform radial gas pressure so long as we can maintain uniform longitudinal pressure in the gas feed channels.

In regard to the thermal resistivity of the impregnated-paper insulation after drainage, it is stated in the paper that measurements show this to be from 10 to 15 per cent higher than the thermal resistivity of solid-type cable. It has been the practice in the United States for some years past to assign a value of 700 to solid-type cable after it is fully expanded by load cycles in service. The gas-pressure cable after drainage of compound accordingly has a thermal resistivity from 770 to 805.

I am afraid Mr. Wyatt has not read the present paper very closely or he would understand that we are not proposing continuous ionization discharge in the cable throughout its life and length. The paper merely presents test data tending to show that at those unfavorable points where incipient ionization might start in service it will be extinguished by self-healing action before real damage is done. This will allow much closer approach to critical ionization in service, than is the case with solid-type cable, without danger of cumulative action at the weaker points along the cable line.

Mr. Wyatt states that in some cases the 30-degree-centigrade "solid" loss increases severely, and goes on to demonstrate that this is due to deleterious by-products of ionization. If this were so, the 80-degree-centigrade "solid" loss would increase even more severely. A study of the test data in the paper will show that this occurred only in test length number 9 for reasons fully explained. In all other lengths tested there is no permanent increase in 80-degree centigrade "solid" loss, and the 30-degree-centigrade increase is actually small and unimportant.

I am sorry I cannot agree with Mr. Wyatt's claims relating to reinforcement of lead sheath for permanent operation at 200 pounds per square inch pressure. We know from a good deal of experience at pressures up to 50 pounds that the problem is more difficult than outlined by Mr. Wyatt.

I would like to thank Mr. Mildner for his interest in the low-pressure gas-filled cable and only wish that I could give him more complete answers to the questions he has raised. Unfortunately, I cannot because Mr. Mildner's whole discussion is based on the supposition that uniformly maintained gas pressure gives no more exact control of ionization than obtained in ordinary solid-type cable where the pressure fluctuates widely with temperature cycles. This is a question that can be fully answered only by operating experience. Laboratory tests and theory both indicate that uniformly maintained pressure does give more exact control of ionization. We all know that ionization discharge is materially influenced by pressure. The whole question is whether this theory will hold under practical operating conditions. Only time and a lot of cable in service will fully answer this question by giving a direct comparison with the service record of solid-type cable.

Mr. Mildner cites a test he has made and offers figure 1 to show that incipient ionization can also be controlled in solid-type cable. I do not doubt that this can be done when all conditions happen to be favorable. The question is can these results be reproduced with every length of solid cable tested? That there is some doubt of this in Mr. Mildner's mind is shown by his statement, "Now while one cannot say at the moment whether it will prove possible to guarantee such characteristics for every production length of cable, these results do indicate that there would seem to be no obvious intrinsic limitation to the performance of solid-type cable." If the low-gas-pressure cable proves to have any real value, it will be based on the hypothesis that uniformly maintained gas pressure will result in a more uniform performance of the insulation and sheath. If this proves so, then obviously we can safely increase the working voltage stress and the severity of other conditions as compared with solid-type cable.

Mr. Mildner is correct in stating that it is better to deal with maximum voltage stress than average voltage stress. Most of the cable lengths we tested had compact sector conductors with relatively sharp corners. For conductors of this shape it is difficult to express maximum voltage stress accurately, and it is for this reason that average voltage stress is generally used as a practical yardstick in the United States.

Referring to the last paragraph of Mr. Mildner's discussion, I offer the following tentative explanation for the variations in the 80-degree-centigrade solid loss of the gas-pressure-cable test lengths. The same characteristic has been noted in solid and oil-filled types of cable and is known to be directly related to the amount of impurities in the cable, particularly the amount of oxidation impurities. To identify this characteristic some engineers designate it as an "oxidation cycle." The theory is that during the initial active stage of oxidation the solid loss increases until finally all oxygen is consumed. After this the solid loss decreases as the final oxidation products become fixed or precipitated. These fixed oxidation products are not actively conducting and explain the decrease in loss.

Symposium on Operation of Boulder Dam Transmission Line—General Operation of Transmission Line

Wm. S. Peterson

Insulation and Lightning Protection

Bradley Cozzens

Discussion and authors' closures of two papers of a symposium presented at the AIEE Pacific Coast convention, Portland, Ore., August 9–12, 1938, and published in AIEE TRANSACTIONS, 1939 (April section) pages 131–56. Other discussion was published on pages 156–60.

C. M. Longfield (State Electricity Commission of Victoria, Melbourne, Australia): As an Australian who had the privilege of visiting the Boulder Dam project early in 1938, this group of papers is of very special interest to me. It is quite evident from even a casual contact with the designing staff that the principles upon which all components of this scheme were based were carefully checked before a final design was adopted. This aspect, and the courageous manner in which it was done, even more than the magnitude of the undertaking, are the things which impress one most, and the electrical industry is very much in the debt of the Bureau of Power and Light for making public both the design and operating results of this undertaking.

Mr. Peterson gives some very interesting data on page 134 of the results of several interruptions. In the case of the trouble experienced on March 29, 1938, he says that Boulder was carrying 230,000 kw. Did this result in a major shutdown in Los Angeles? As I understand the situation, Boulder carries a very large percentage of the total load in Los Angeles, and the erection of a third line will increase this percentage. What provision is being made for maintaining emergency supply in the event of major interruptions on the Boulder transmission line?

It appears that, so far, relay operations from one cause or another have always resulted in tripping off both circuits. This seems to have been due to:

(*a*). Both circuits being damaged by a tower wash out,

(*b*). Switching surges on parallelling circuits, or

(*c*). Faulty relay wiring.

In other words, from an operating point of view the reliability of the line has so far not been improved by having two circuits. Had these circuits been mounted on separate towers and paralleled at a lower-voltage bus, one circuit might have remained in service at least when the load being carried was within the transient stability limit of the remaining circuit.

The high efficiency of the line is a striking feature of the paper, and revival of the use of variable voltage at the generators is of particular interest. Have the losses in the synchronous condensers been included in calculating the efficiency of transmission listed in table I?

It is not generally realized how important the distribution of voltage along a transmission line can be as affecting the size of synchronous condensers. This is especially noticeable in those cases where intermediate condensers are used when the optimum set of conditions is highly critical.

In discussing lightning protection, Mr. Cozzens says that "ground resistance measured on stakes driven to approximate counterpoise depth showed resistance values as high as 3,000 ohms." Is this the resistance to ground of a single stake driven to this depth, or is it the soil resistivity as measured, say, by the Gish-Rooney method? The continuous counterpoise as used on the Boulder line is a very expensive construction, and one would naturally want to avoid the expense involved if a discontinuous counterpoise would do. For a line of the type described, but more favorably situated as regards ground resistivity, what would the author regard as a limiting resistance above which a continuous counterpoise becomes necessary? A very striking feature of the design of this line is the immunity from flashovers during the lightning storms so far experienced and which have left unmistakable evidence of their severity in the burning of the gaps. Is it safe to assume that the majority of discharges which cause burning of the gaps have been direct strokes to tower structures? Why is it that the magnetic links on the lightning arresters have shown no appreciable evidence of discharge? Is there then no evidence to show that the lightning arresters themselves have functioned? If not, why?

On the evidence so far presented, one could summarize Mr. Cozzens' paper by saying that the lightning protection provided has produced a line which, for all practical purposes, is trouble-free. It at least appears that the line is immune from interruptions due to lightning and that with periodical cleaning of the insulators in certain sections the line should be free from insulator failures due to foggy conditions. This conclusion, if valid, is an important one since, in that case, it would be possible to put reliance in a single-circuit line where it would otherwise be uneconomical to erect a duplicate circuit.

The influence of high-speed operation of relays and switchgear is also of great importance, as has been emphasized by E. H. Bancker in the discussion. Indeed the effect of rapid clearing of faults is very profound, especially in those cases where the transmission line delivers only a part of the total load into the network. Whether an additional circuit can be dispensed with will depend upon what provision has been made for taking up the load dropped by the faulty line and the transient stability characteristics of the rest of the system. This brings me back to the point raised in the second paragraph above, namely—what provision has been made in Los Angeles for supplying that part of the load dropped by the loss of one or both Boulder circuits?

W. S. Peterson: We greatly appreciate the interest that Mr. Longfield has shown in this project so remote from his immediate operations, and value greatly his contributions in discussion.

In reply to the question concerning the outage of March 29, 1938, the rolling reserve at the time of the trouble was sufficient to carry the entire system load, even if the Boulder plant were dropped. However, during the trouble and before the Boulder plants were disconnected, the frequency had fallen from 60 to 48 cycles. While the remaining generators were picking up the system load, the local load at station *B*, where Boulder power is received, was dropped, to facilitate the speed increase so synchronizing with Boulder could be accomplished. The amount of load dropped was approximately 50,000 kw. The remainder of the system load was carried without interruption.

The additional circuit from Boulder travels an entirely different route from Victorville switching station to Los Angeles. It is felt that this will give added protection to the Boulder power. Additional steam facilities will have to be provided in the near future to furnish load demands as well as stand-by service for the transmission systems. However, it is not the intent to provide 100 per cent Boulder system stand-by at the time of the annual peak load. Sufficient stand-by will be used to permit the leaving out of one section of circuit (90 miles) and be ready for a switching operation on another 90-mile section without losing synchronism. Due to the high standards of construction of the Boulder transmission system, it is believed that the service under such conditions will be superior and the investment less than would prevail if lower standards of line construction and 100 per cent steam stand-by were used.

Mr. Longfield's statements are true regarding the causes for outages, but it should not be misconstrued that the switching surges were of the type to cause flashover. They were, rather, current transients that operated on the relay circuits such as to indicate a faulted line and cause false tripping. Also, the major sources of trouble were the errors of human operation. It is true that to date the relays have failed to clear the faulted line without also dropping the parallel good section, but it is anticipated that this will be overcome in the very near future. The undesirable features of two circuits on one tower line were recognized, but right-of-way expense made the use of two tower lines prohibitive.

As stated on the bottom of page 133, the efficiency given in the table includes the losses through the autotransformers and the synchronous condensers, but does not include the loss in the transformation from 132 kv to the distributing voltage of 33 kv.

Bradley Cozzens: In reply to Mr. Longfield's question concerning the high values of ground resistance, these values were determined with the three-electrode Meggar method, using two of the electrodes as the current-carrying elements and a third stake to determine the potential of the ground as uninfluenced by the flow of current. This method is that outlined for use with the ground Meggar in Bulletin 1285 of the James G. Biddle Company.

In regard to the cost of continuous counterpoise as compared to the radial or other type, it is true that where the country is mountainous, rough, or of a solid rock formation, the continuous counterpoise is the more expensive. However, where the country is not extremely rough and will allow the use of the large counterpoise-laying plow, the cost of the continuous counterpoise is probably less than the actual cost of radial counterpoise with terminating ground rods, and is felt to be much more effective. We have not had sufficient experience to state at what ground resistance counterpoise should go from radial to continuous type. Future flashovers, if and when they occur, may give the answer to this question.

It is certain that practically all of the burns on the counterpoise gaps were caused by direct hits to either the tower structures or the ground wires. The few exceptions to this might be where the transmission line crosses lower-voltage circuits, and these circuits may have discharged into the counterpoise system and caused some of the smaller burns observed. The strokes to the towers have not as yet flashed gaps more than four towers from the tower contacted by the stroke.

With regard to the operation of the arresters at Boulder, we have had no direct hits within the first mile from the Boulder switch rack, so it is relatively certain that any of the more remote strokes would not have induced the 825 kv in the conductor which is necessary to cause operation of the arresters. The only indication of operation of the arresters is the slight burning of a series paper-film gap, but this has been attributed to the arcing of the disconnect switches connecting the arresters to the 287-kv bus.

Mr. Longfield's comment concerning immunity from lightning will have to have a slight prefacing, for on March 22, 1939, the Boulder north line was flashed over by lightning. This was the first flashover out of over 200 recorded direct hits. There is some consolation in the fact that it was a hit of the "unusual" type. The stroke apparently contacted the top arcing horn of a suspension string and with the heavy ionization accompanying such a condition bridged the string. This occurred with the ground wires located just $7^1/_2$ feet inside the vertical plane through the outer conductors and 30 feet above them at the tower. Such conditions, of course, cannot be predicted or guarded against. The arc formed directly between the horns and there were no burns on any of the insulators.

We, again, wish to thank Mr. Longfield for his interest and contributions to the papers.

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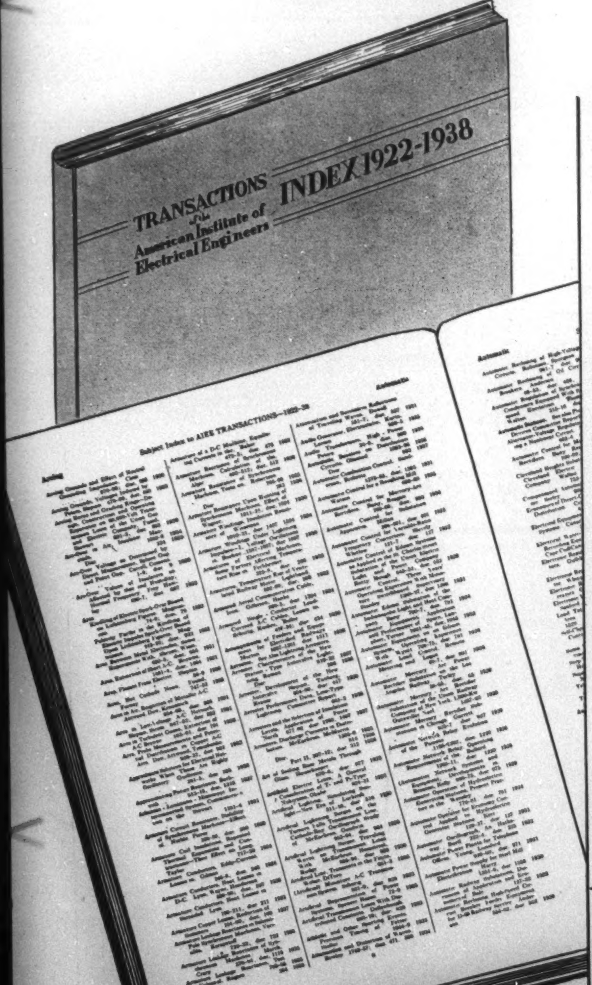

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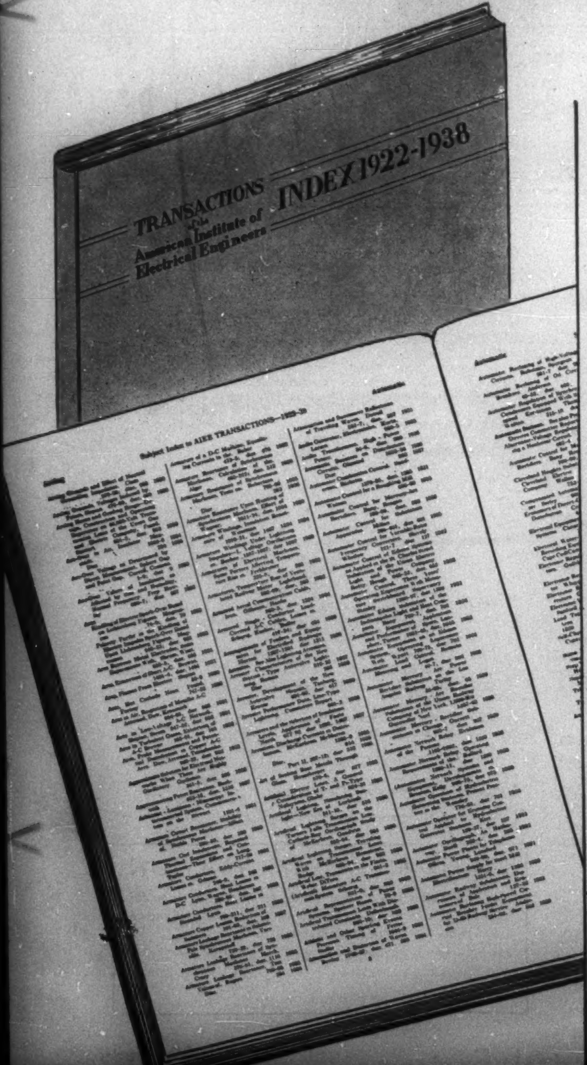

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Six such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6 Mercury Arc Rectifiers.
25 Fuses Above 600 Volts.
501 Test Code for D-C Machines.
40 Electrical Recording Instruments.
— Test Code for Transformers.
— Test Code for Synchronous Machines.

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